Novel tools for measuring jets in heavy-ion collisions

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Wright Laboratory

Yale

Measuring jets in HI collisions

- Many challenges for measuring jets in heavy-ion collisions:
  - ➡ Large underlying background in heavy-ion collisions that is very difficult to remove
    - ▸ Restricts measurements at low jet p_{T} where we are still interested in the physics
    - ▸ Prohibits unfolding due to large back contribution in the response which makes it difficult to compare directly to theory and constrain jet quenching models
  - ➡ Difficult to find variables that are sensitive to the physics we are interested in i.e. using jets to probe the QGP
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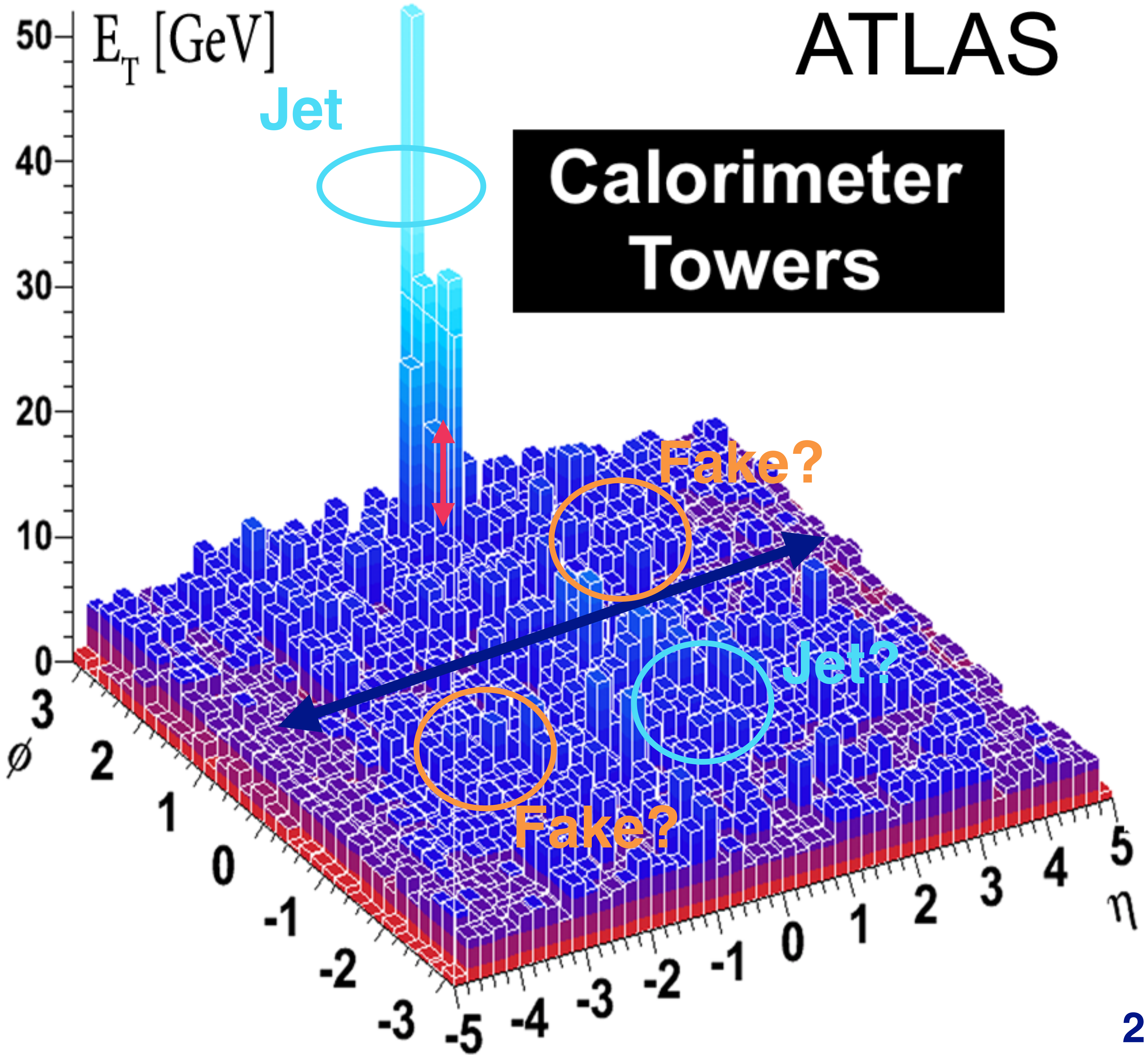
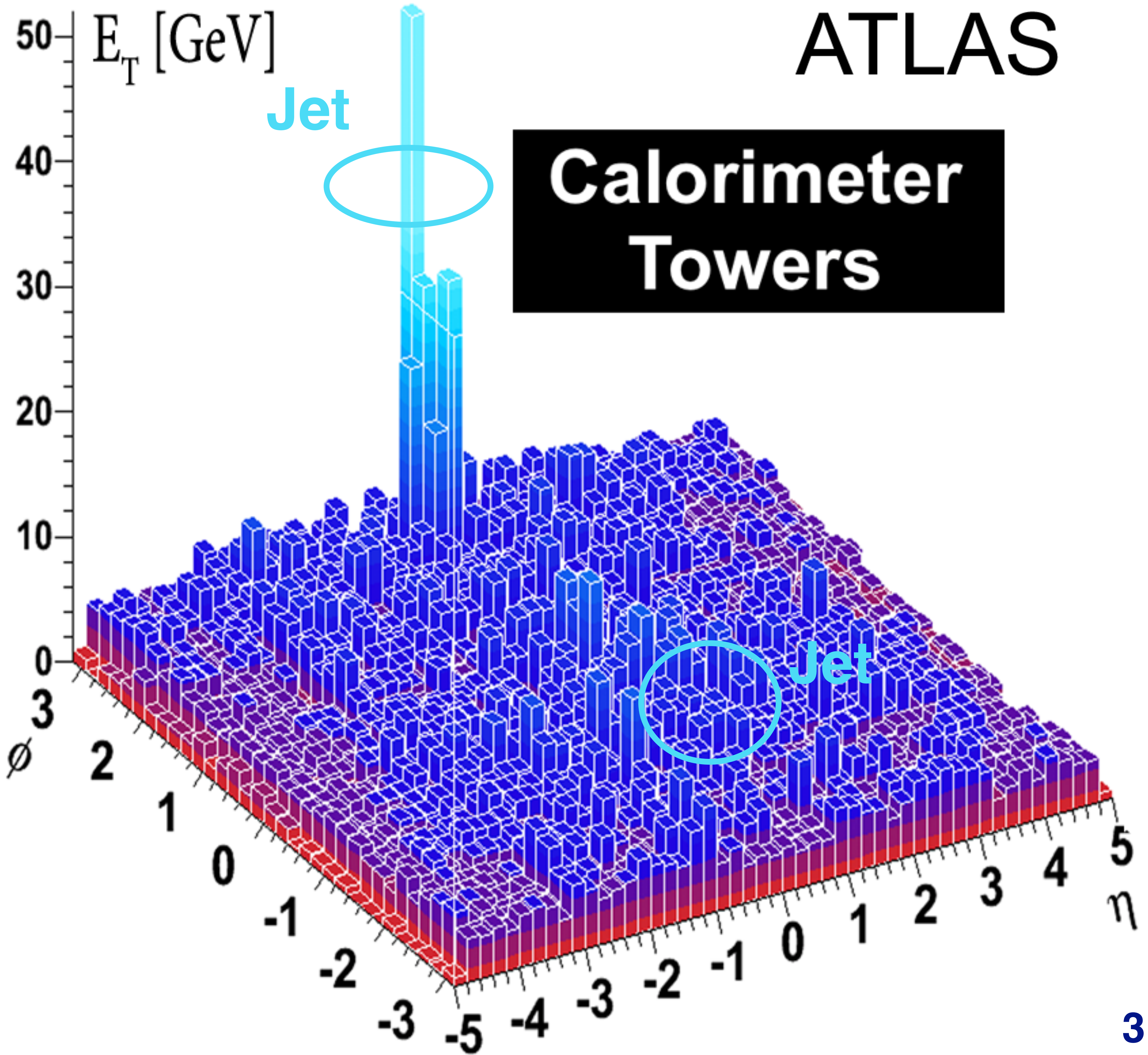
Heavy-ion background

- Large uncorrelated background due to the underlying event (UE) that contributes energy inside the jet cone
  - Fluctuating greatly with η and Φ and event-by-event
  - Can be of the order of the jet itself
- Have to effectively remove the energy from inside the jet and also be careful with fake jets due to upward fluctuations



Background subtraction

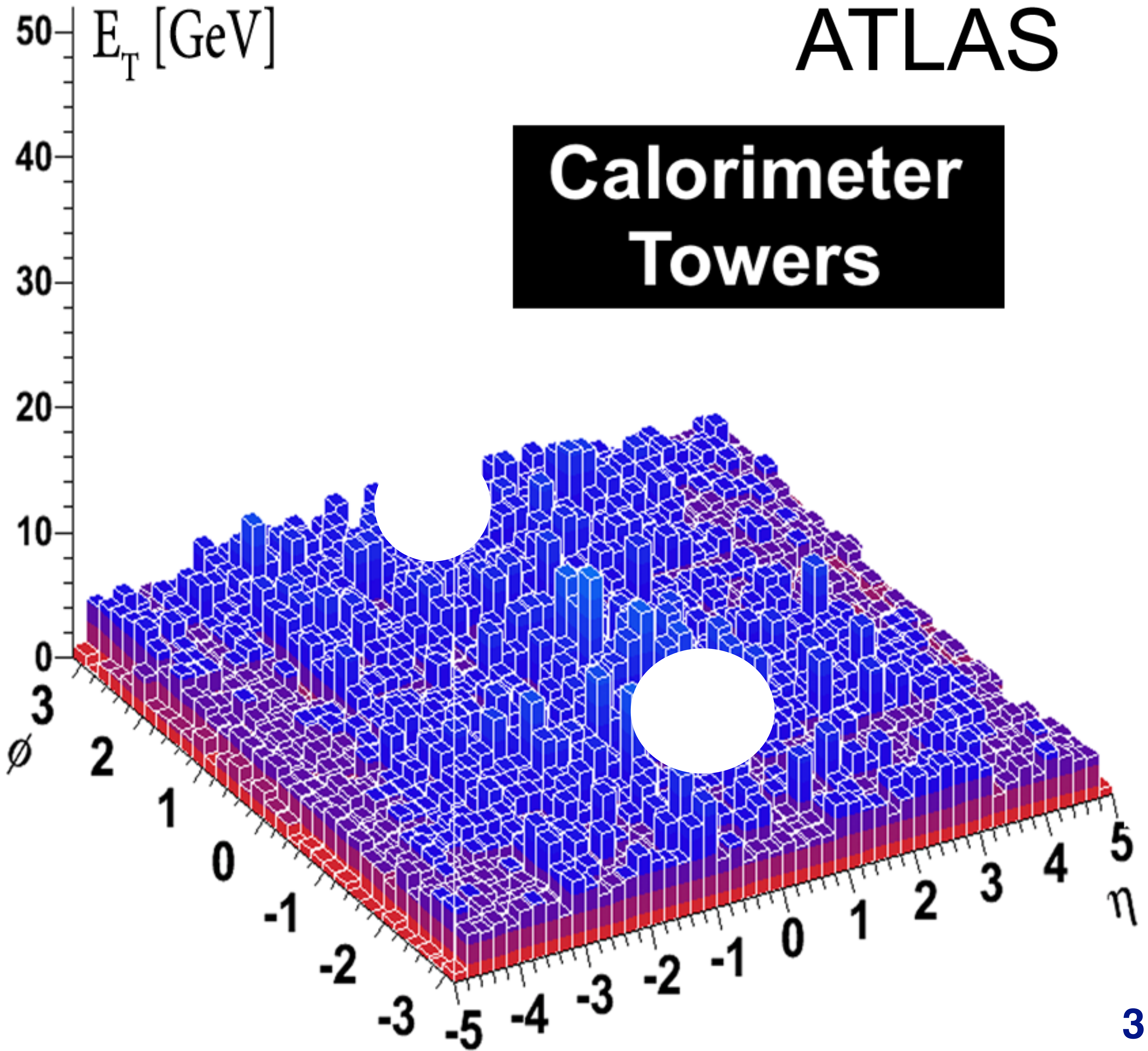
1. Find two highest jets



Background subtraction

1. Find two highest jets
2. Remove jets

ALICE



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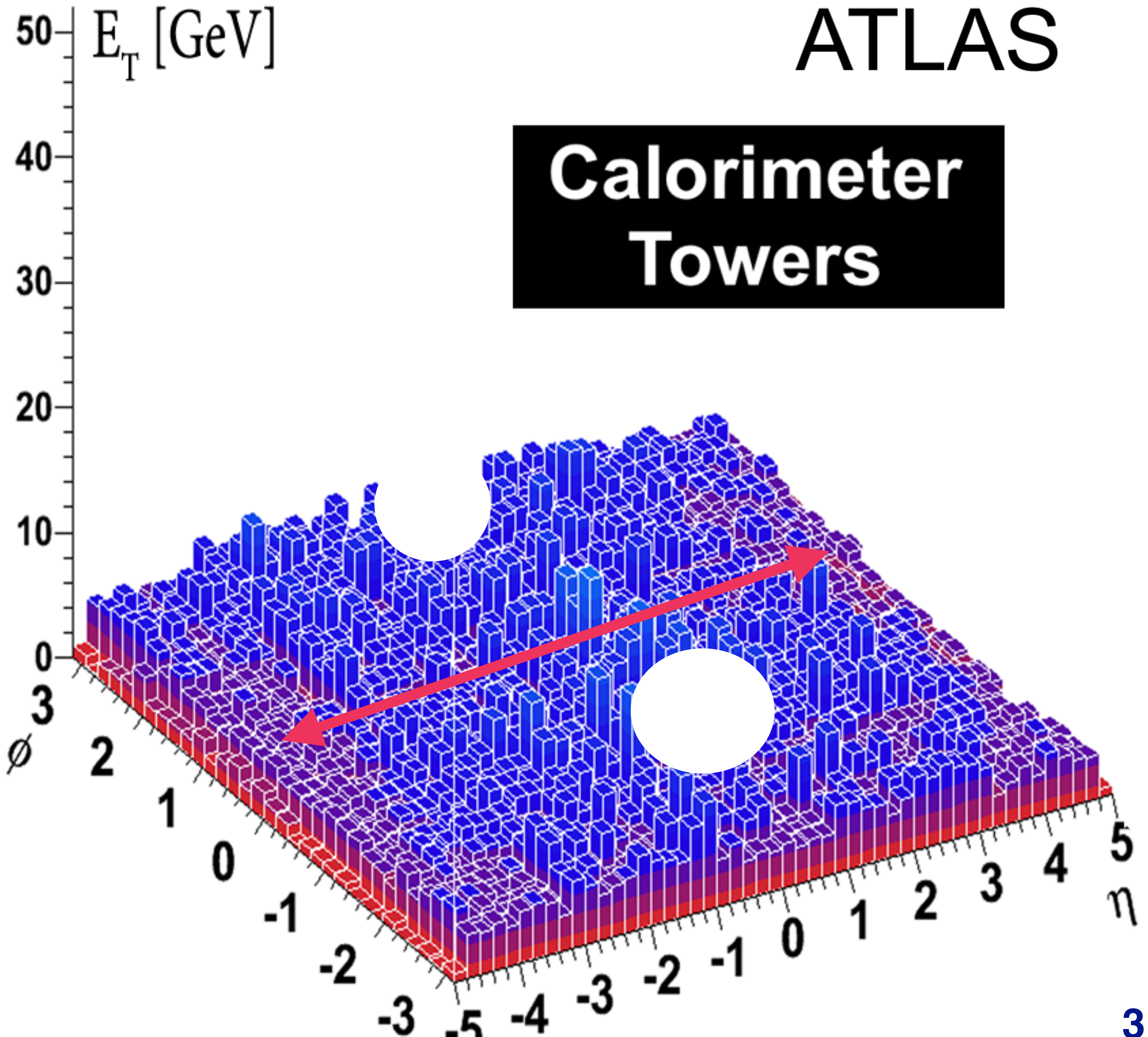

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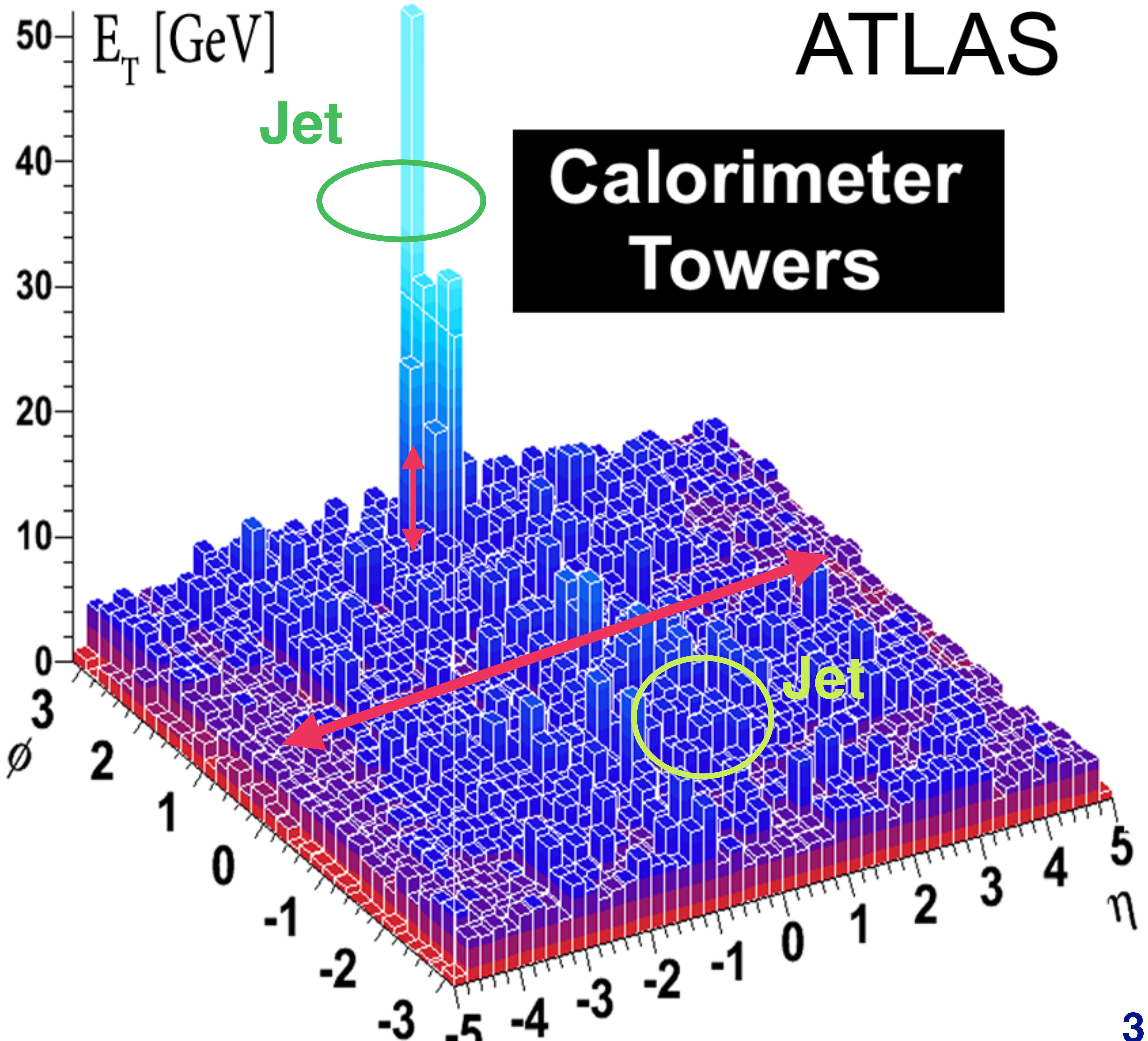

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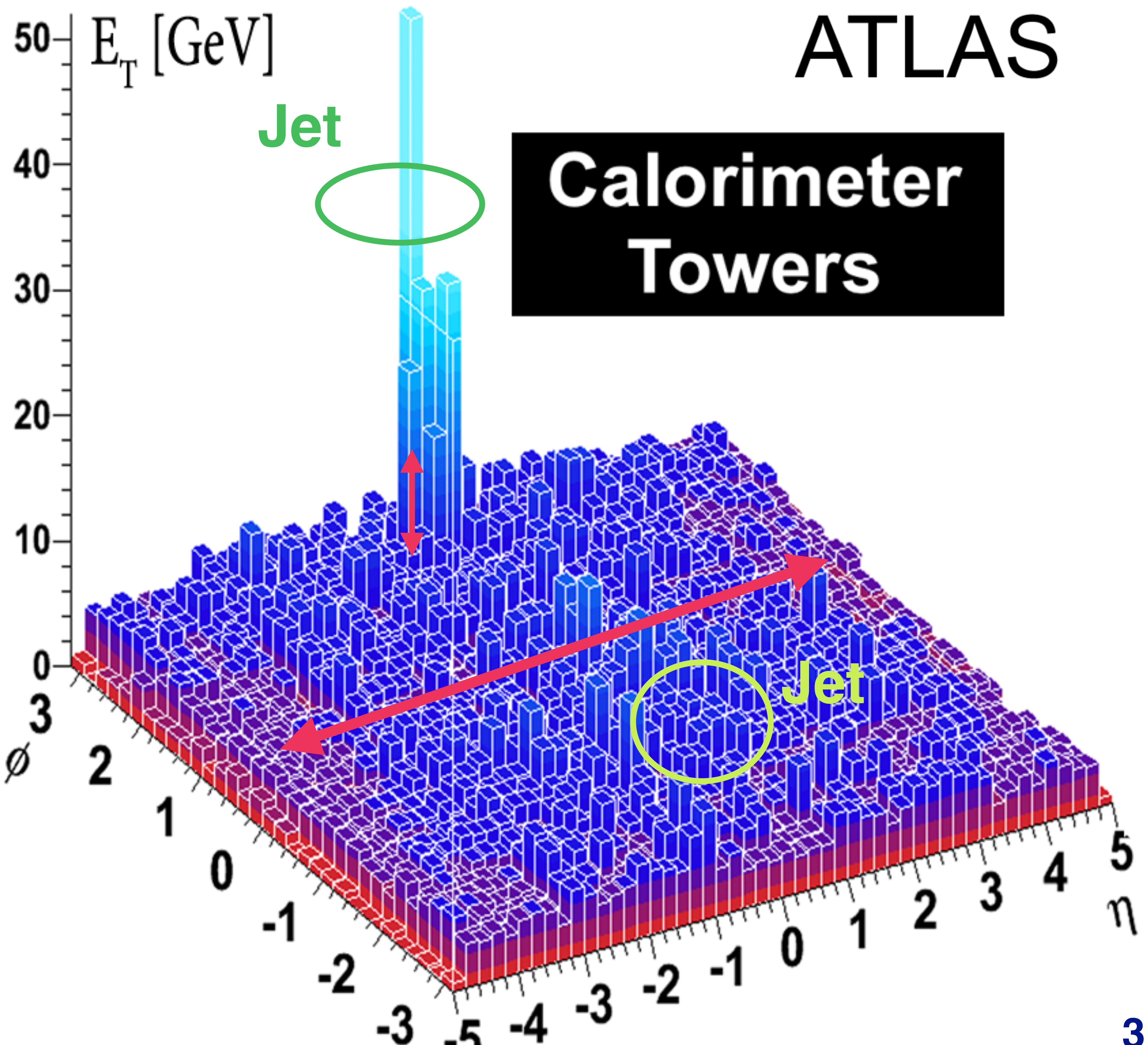
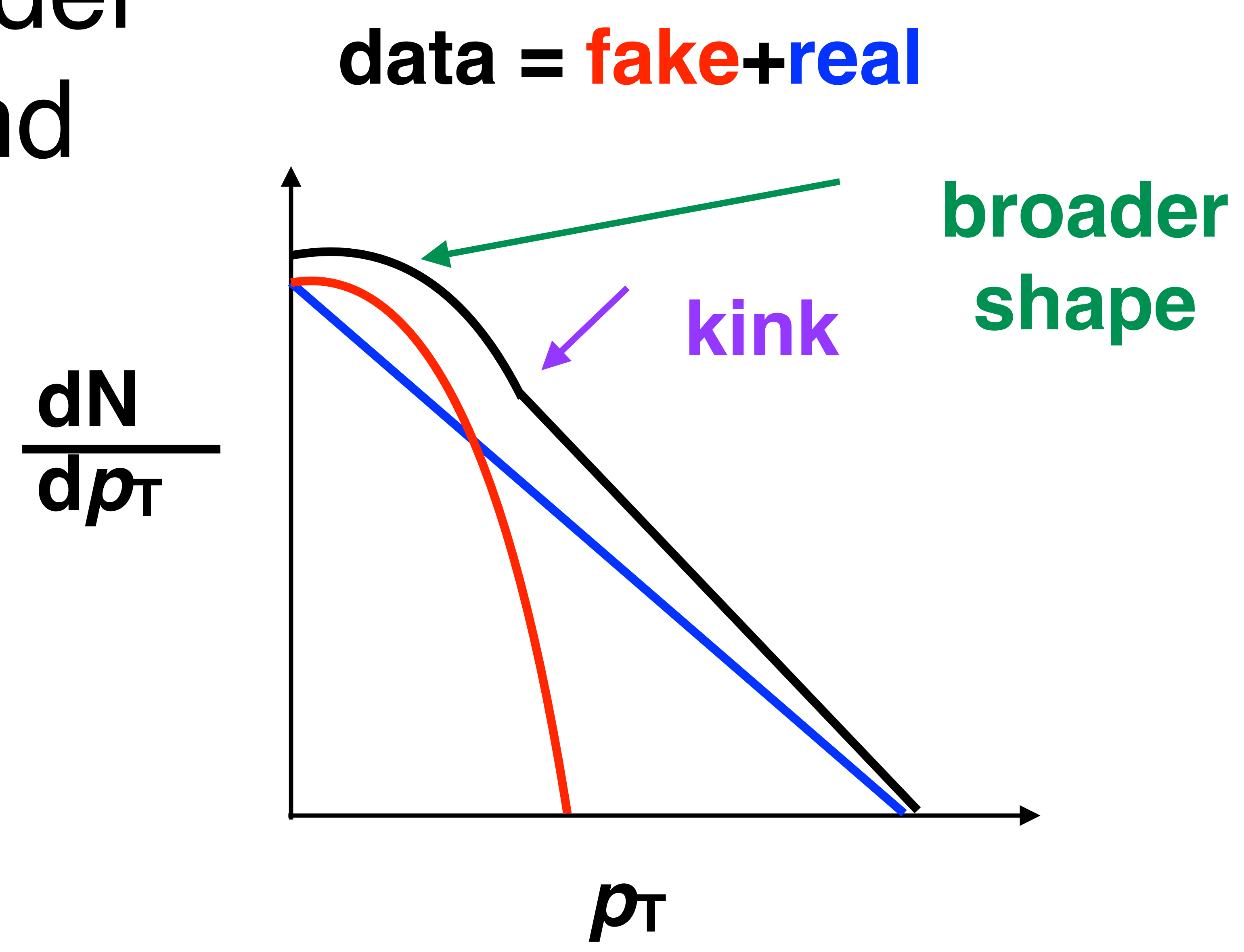


Leading track bias: only include jets with a hard core

Jet measurement limitations

- Challenging to go to larger R or low jet p_T due it being harder to remove the background leading to a large resolution and "fakes", making unfolding difficult



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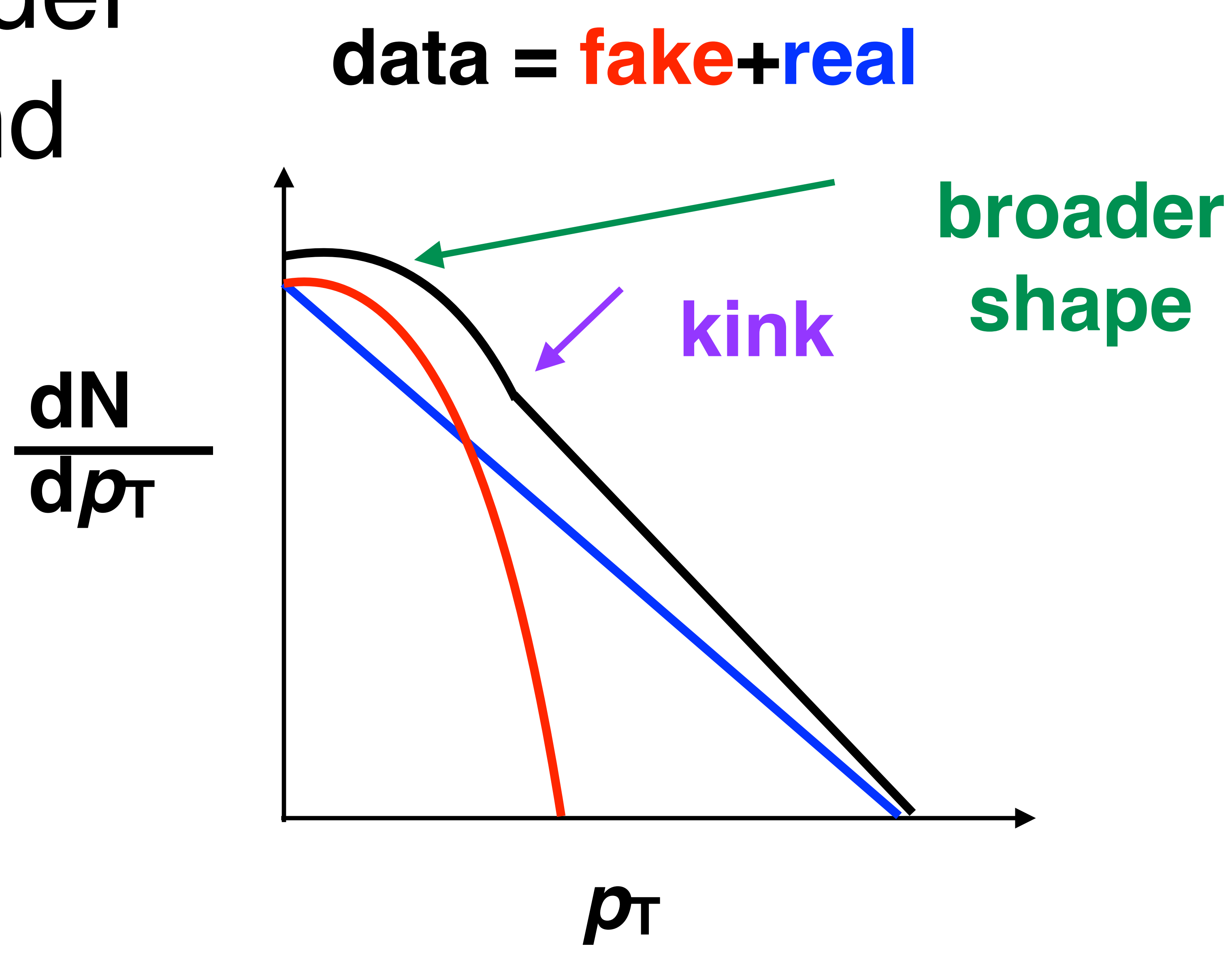
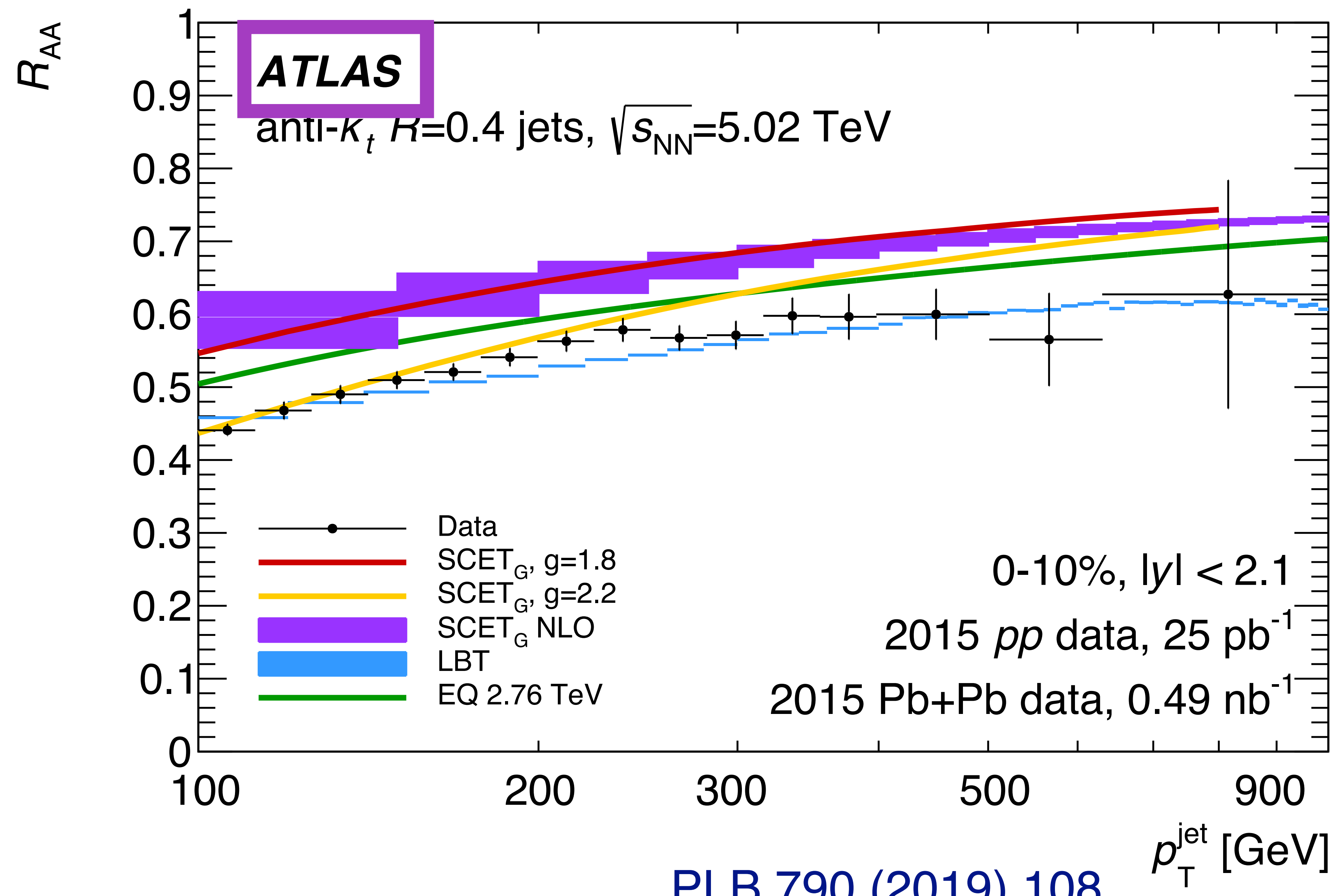
ATLAS /CMS measure jets down 100 GeV and up to 1 TeV





PLB 790 (2019) 108

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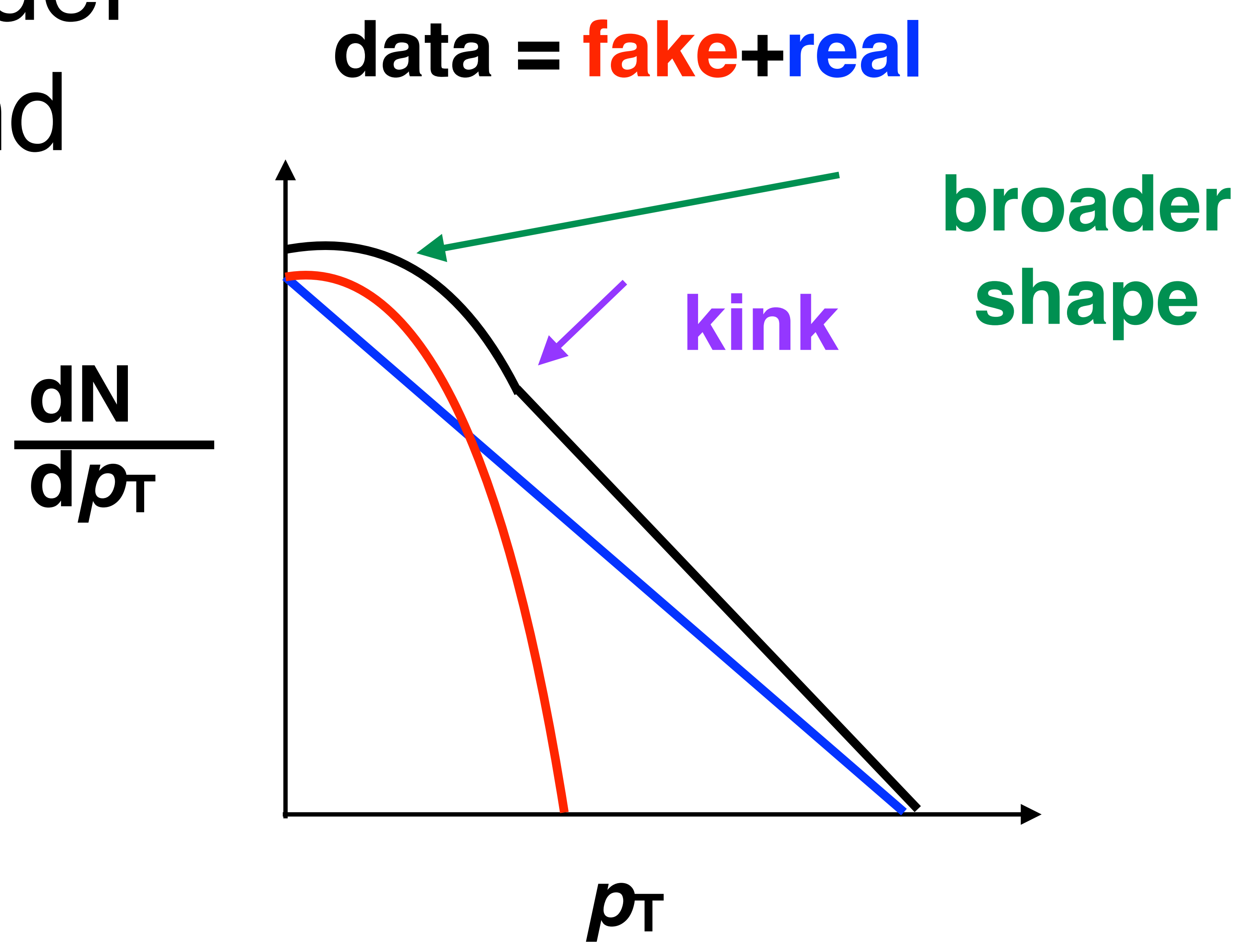

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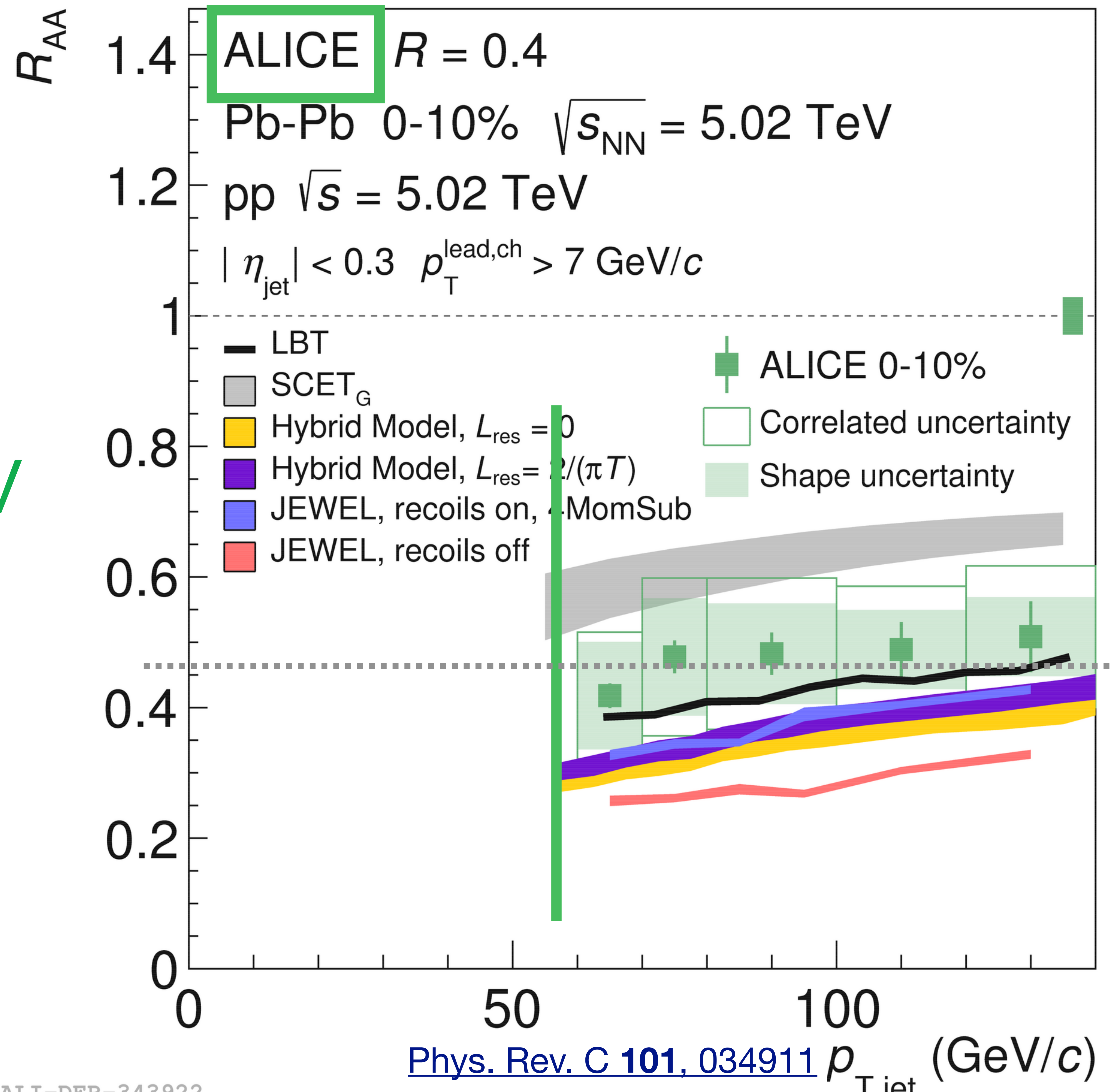
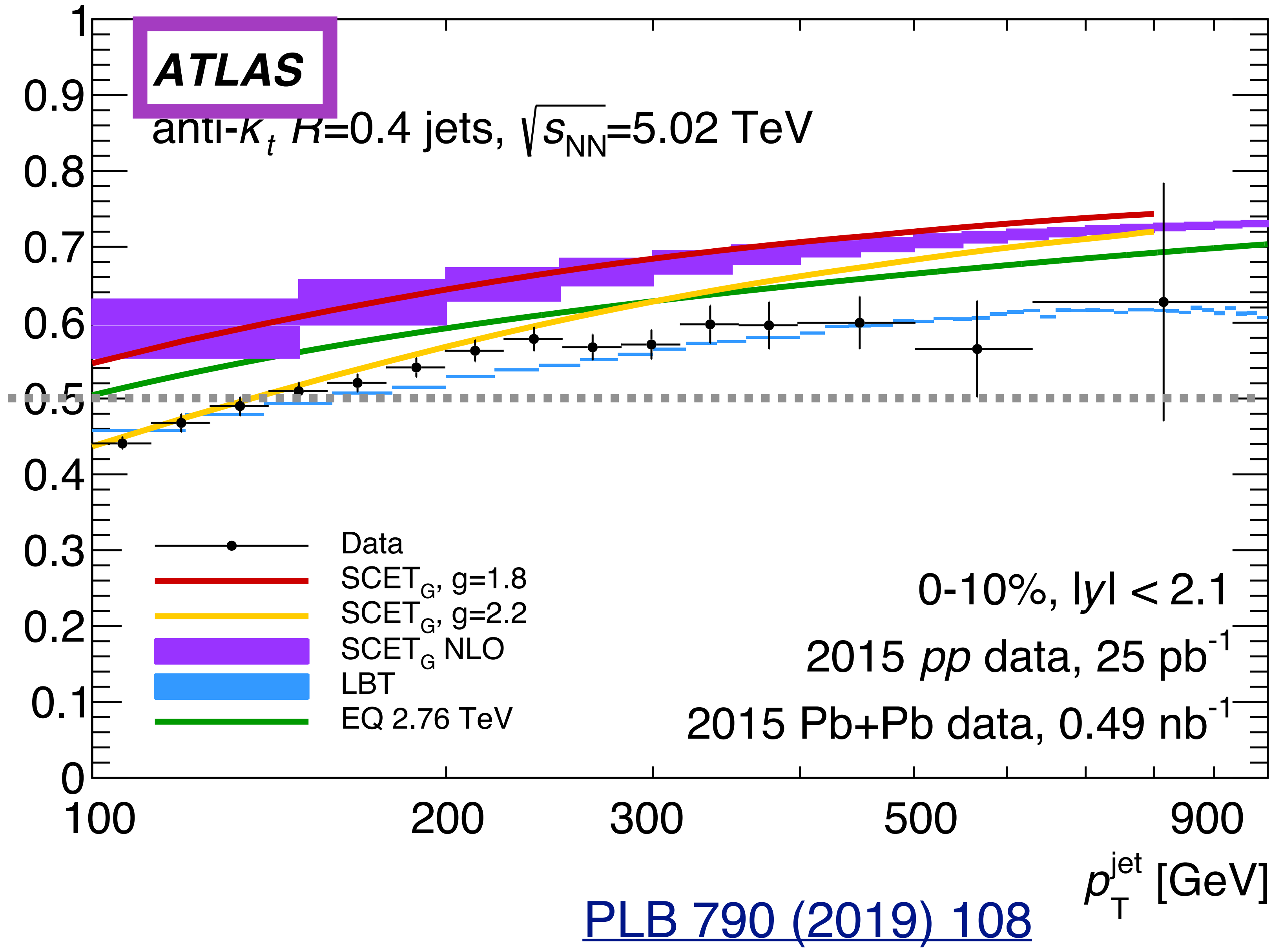


Phys. Rev. C **101**, 034911



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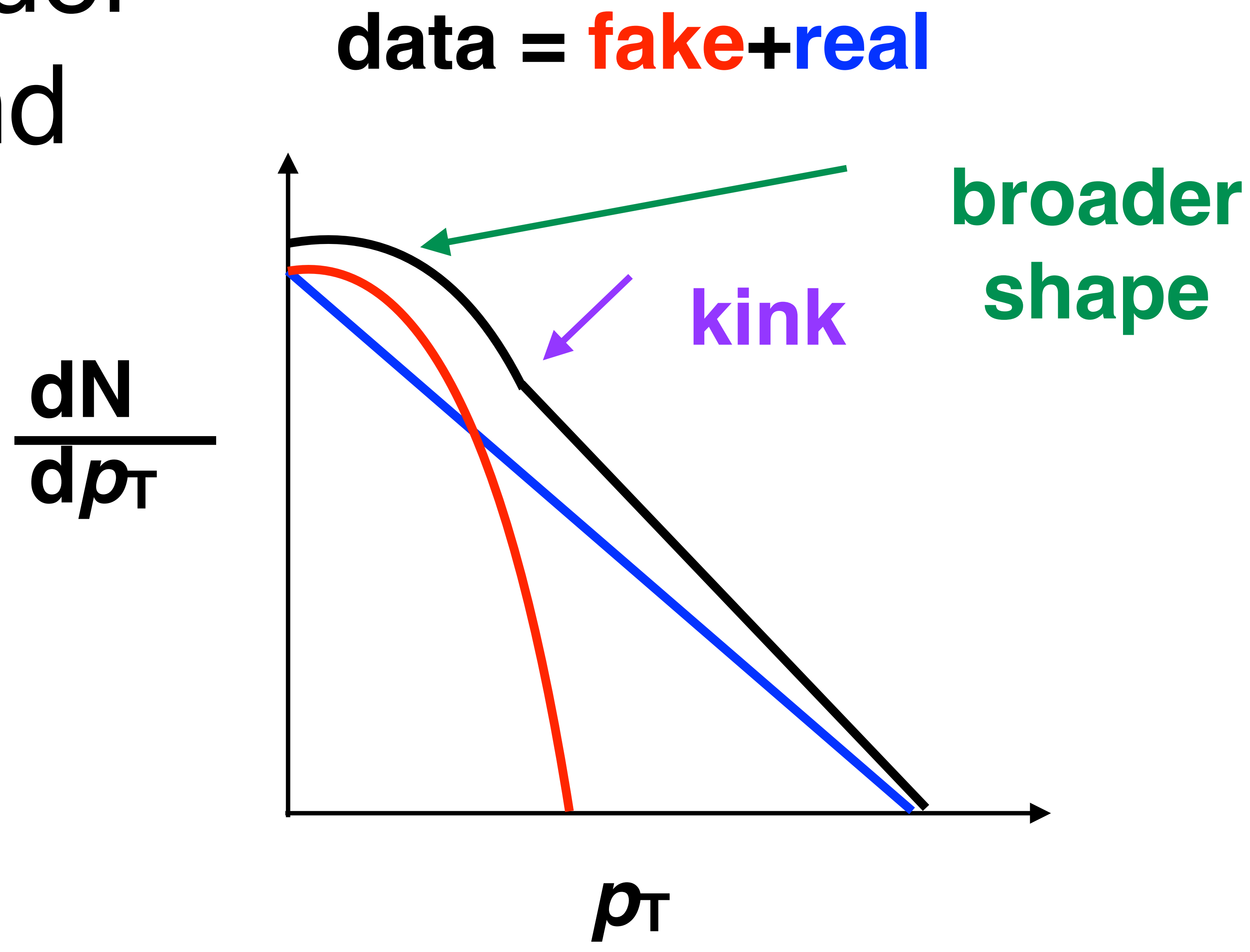

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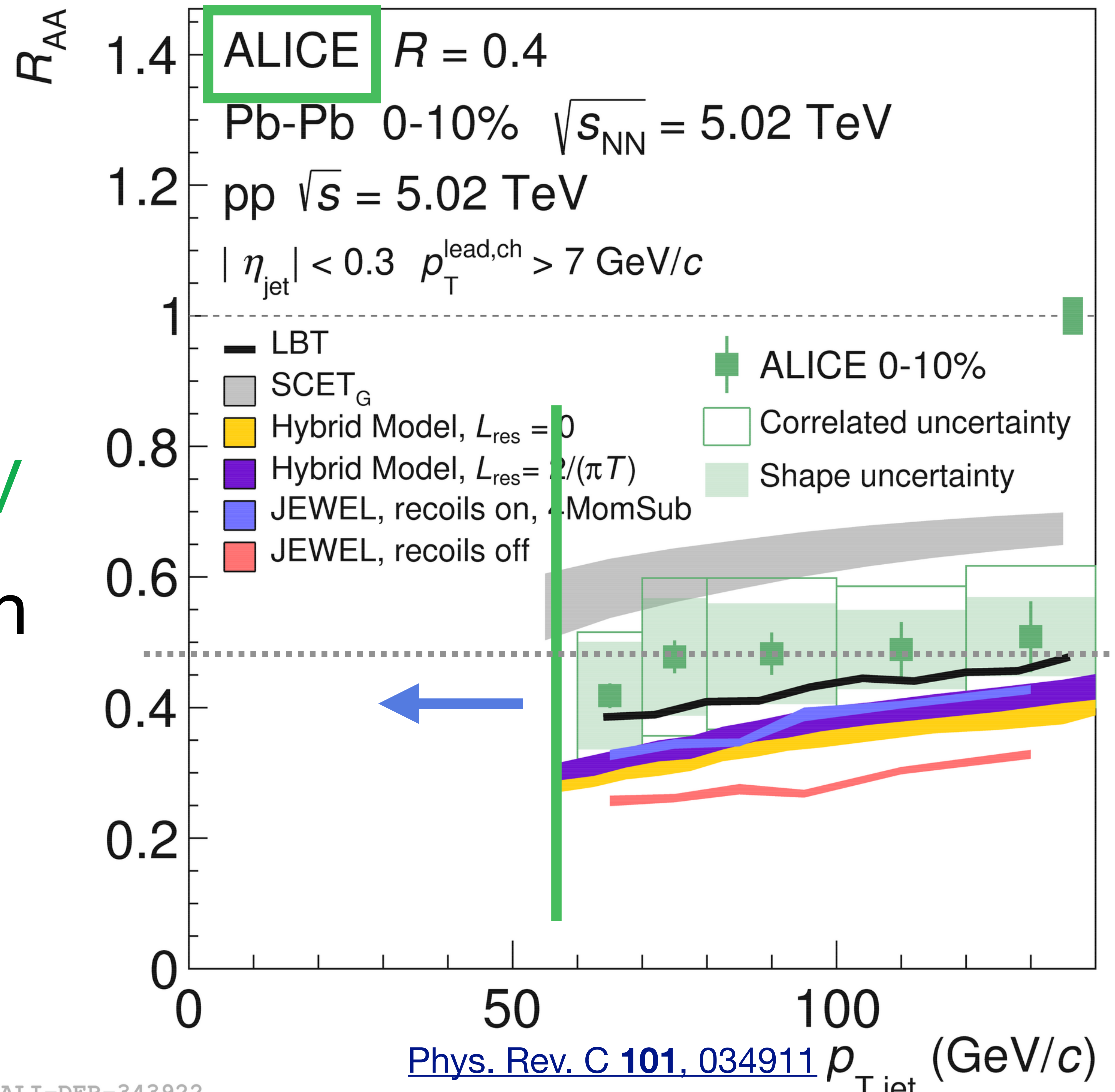
Need more precision and lower p_T to constrain models

ML approach may help!



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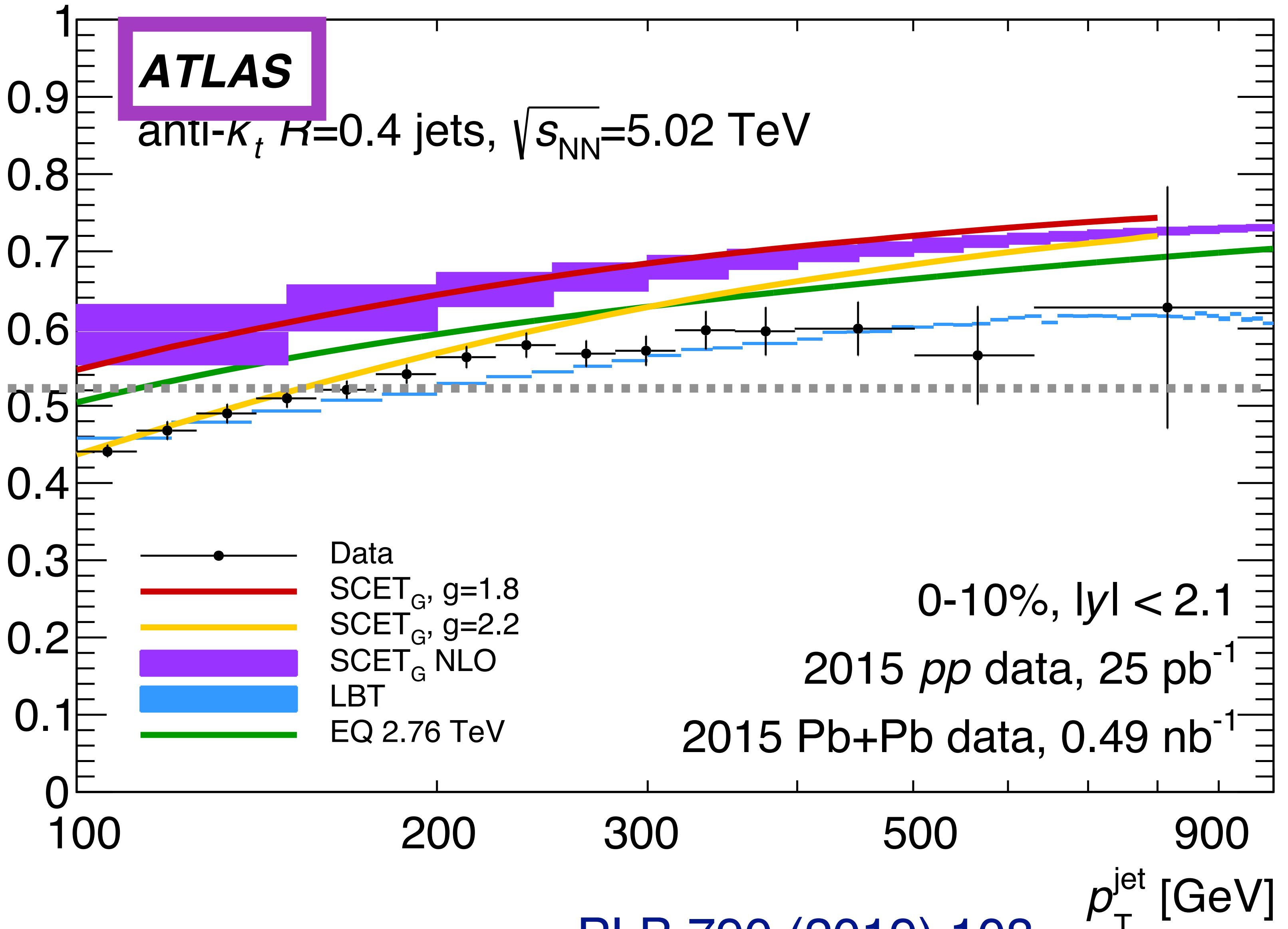

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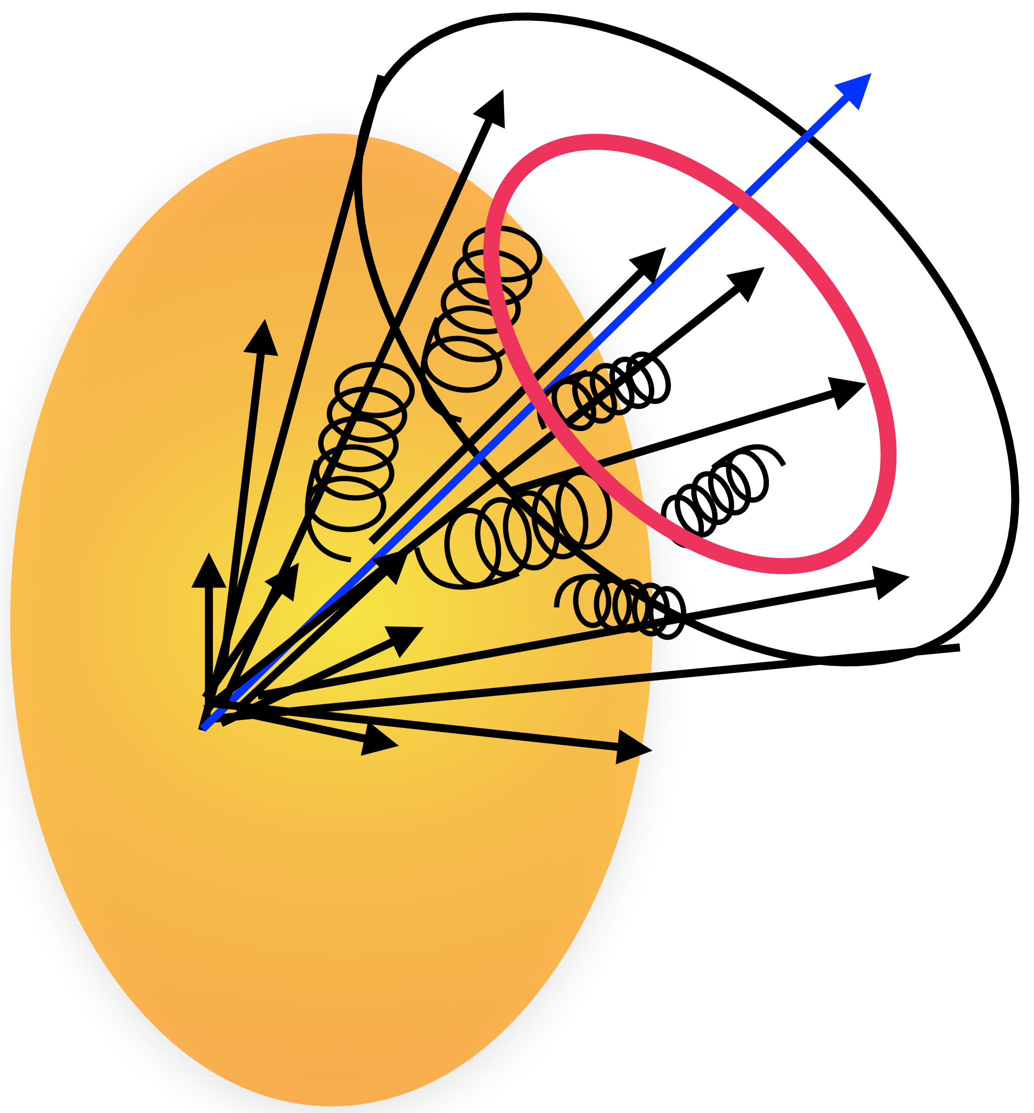
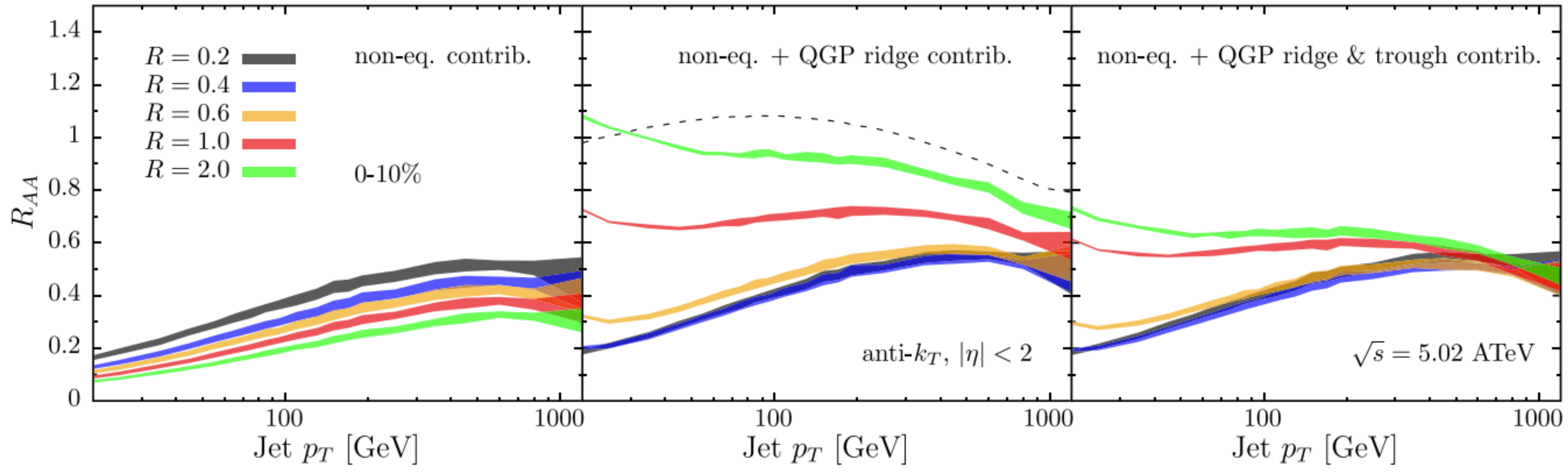
Large R/low p_T motivation

- Larger radii
  - ➡ Possible recovery of the jet energy because of out-of-cone radiation
  - ➡ Possible different in modification for larger jets



- Lower jet p_T
  - ➡ Probes different scale and modification expected to be different
  - ➡ Connection to RHIC
  - ➡ Different quark/ gluon fractions
  - ➡ Difference between jet radii could be larger at lower p_T



Hybrid model

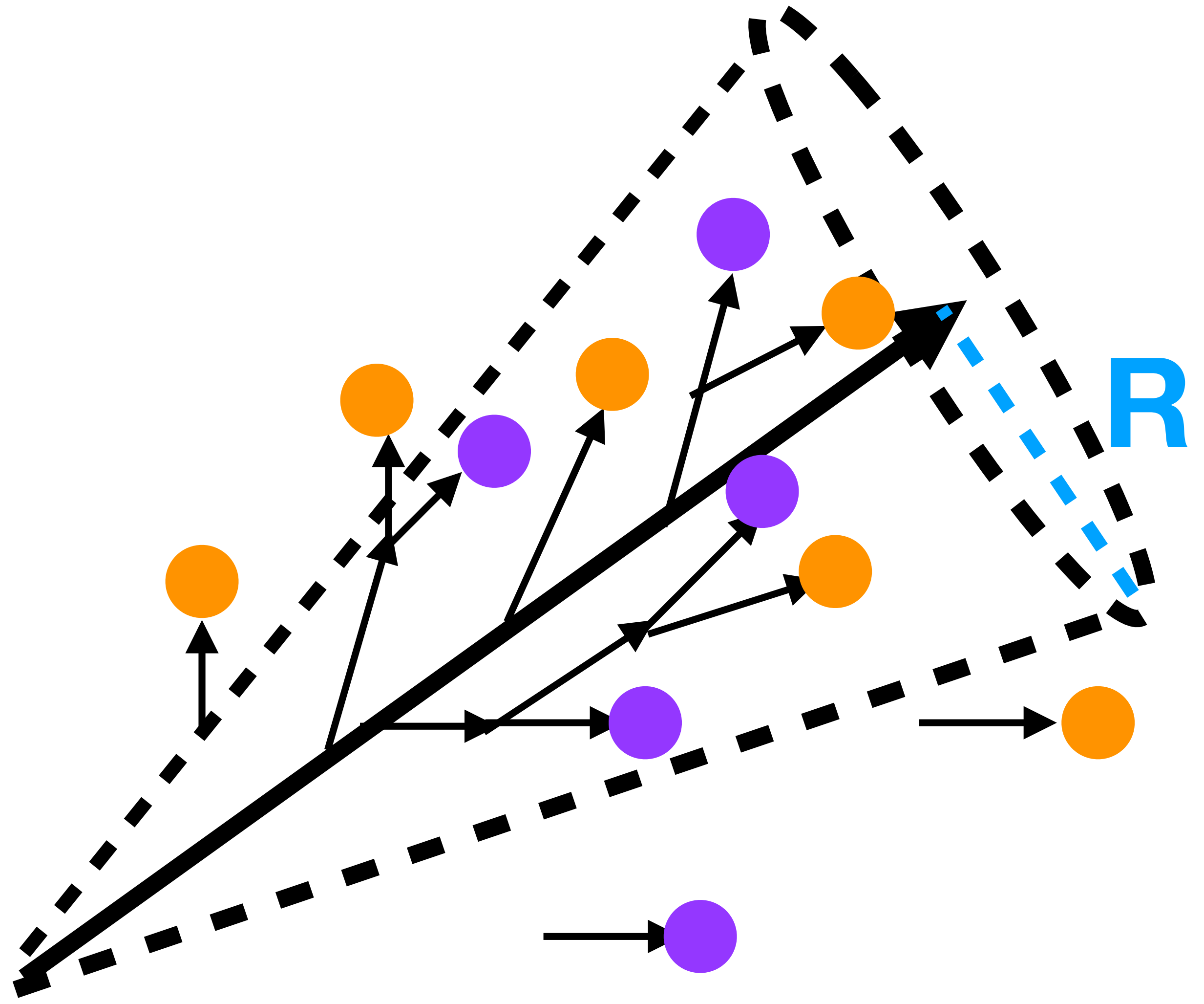
Phys.Rev.Lett. 124 (2020)

Machine learning approach

- Standard ALICE procedure misses residual fluctuations
  - ➡ Oversimplified estimate of rho using entire event
  - ➡ Fakes taken as signal

Phys. Rev. C 99, 064904 (2019)

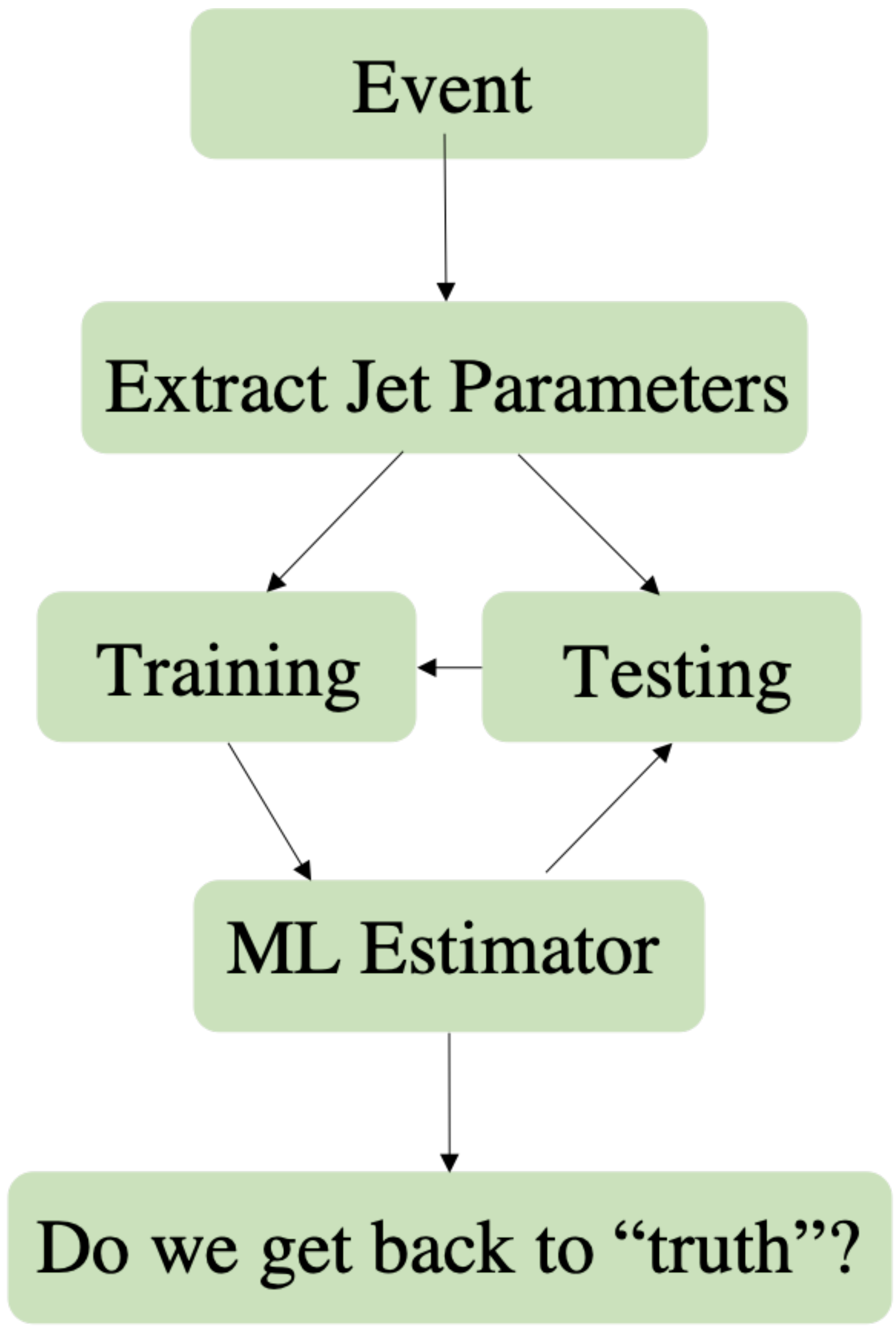
- ML techniques used to learn a data-driven mapping to correct the jet p_T by exploiting the difference between the signal jets and the background jet-by-jet
  - ➡ Reduce residual fluctuations to better determine the jet p_T



Jet properties including standard corrected p_T and jet constituents → ML → Correct jet p_T

- Can be applied to charged or full jets (which contain charged tracks and neutral clusters, measured in the TPC and EMCal, respectively)

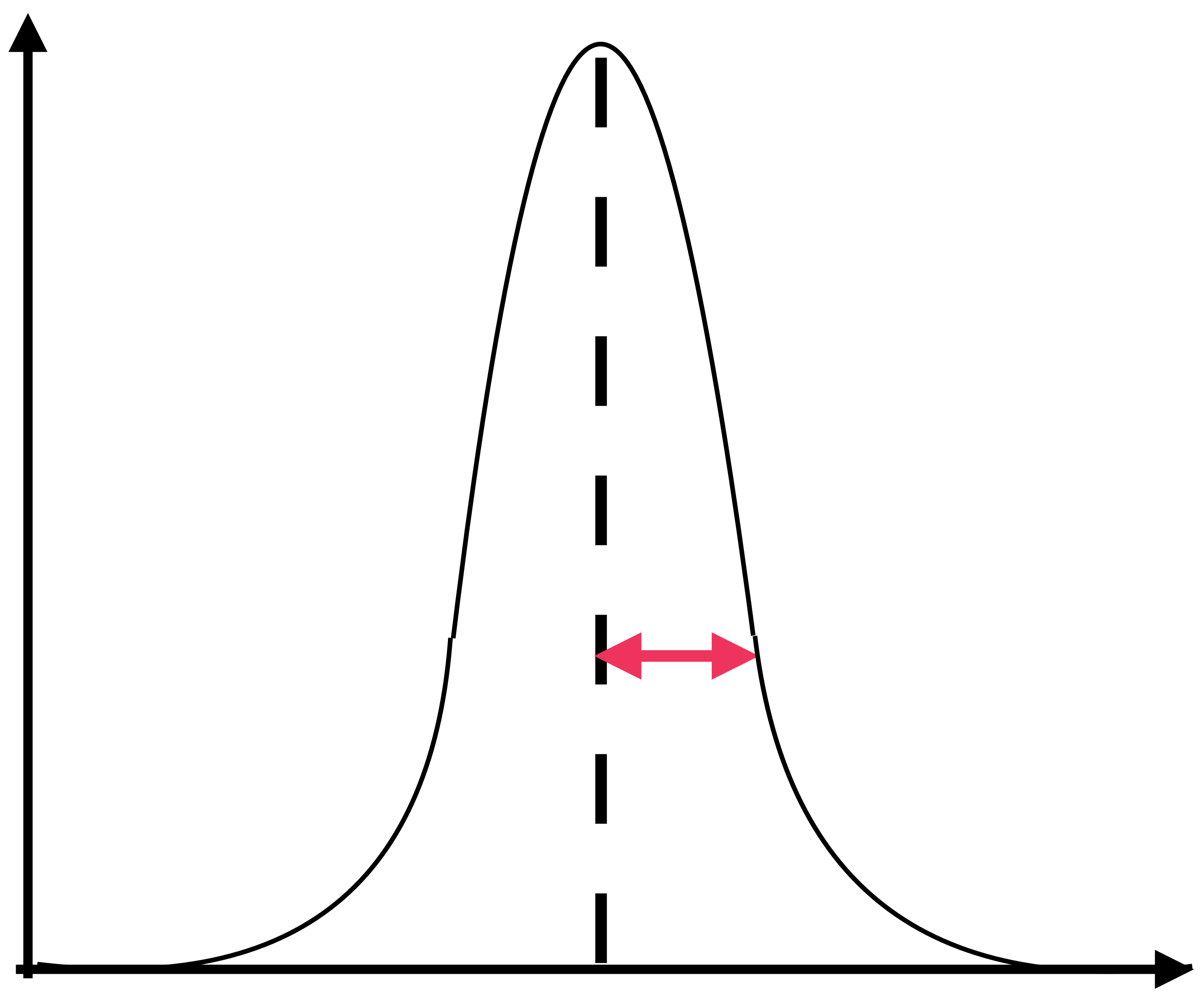
ML approach: method



- A realistic event is made by embedding pp PYTHIA events into real Pb-Pb data or into a toy model background
- Jet parameters extracted, including the area-based corrected jet p_T, jet angularity, p_T of 8 leading tracks, number of constituents
- 10% training and 90% testing
- ML algorithms: shallow neural network, random forest, and linear regression
- Regression task to predict the corrected jet p_T
  - Asking if we got back to the "true" p_T i.e. the detector level PYTHIA jet p_T

ML approach: charged jet performance

- Evaluate the performance by comparing the difference between the ML corrected p_T^{reco} and the “true” detector level p_T^{true}
  - The narrower the width of the distribution the better the resolution



$\Delta p_T = p_T^{reco} - p_T^{true}$

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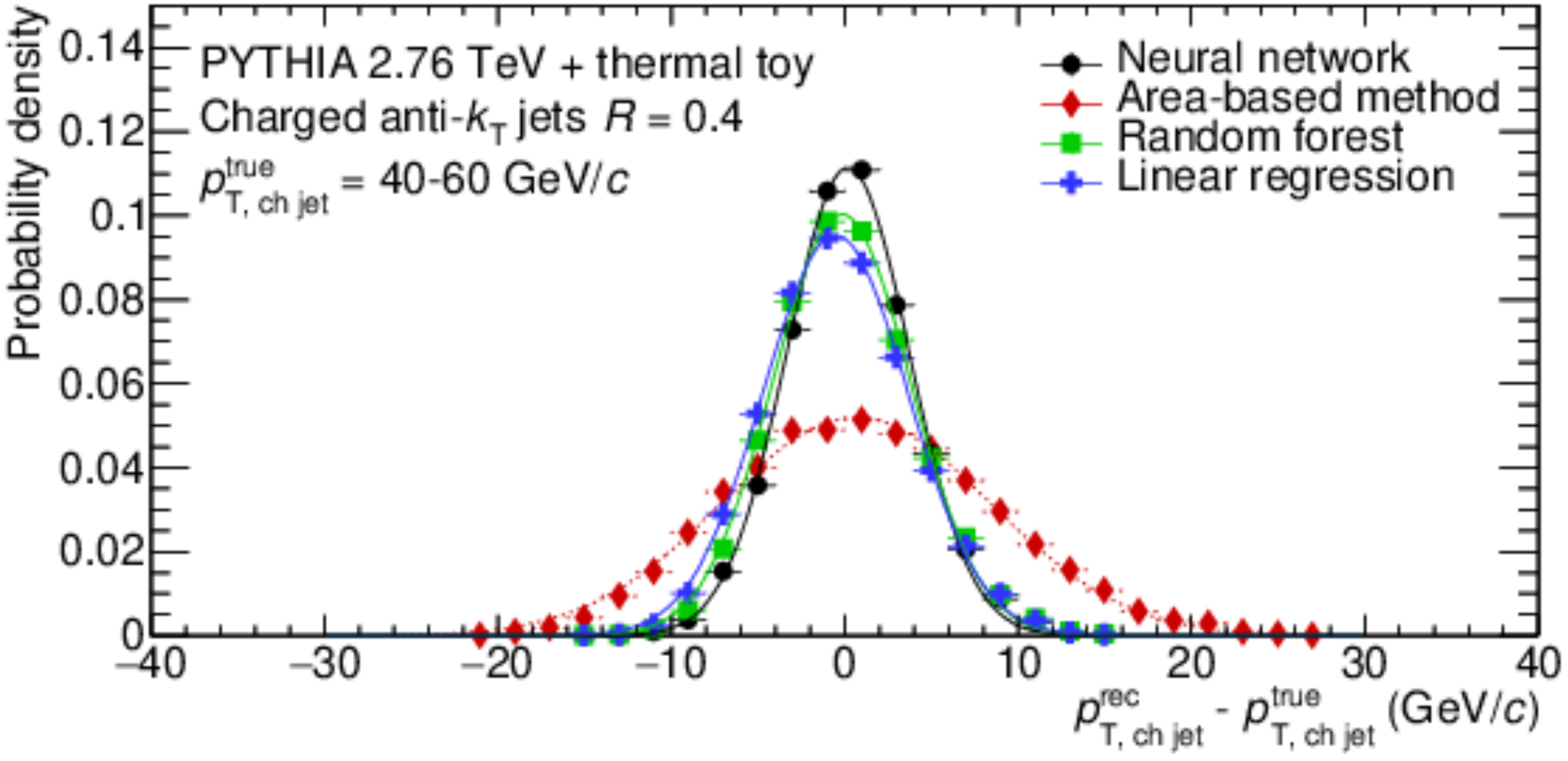
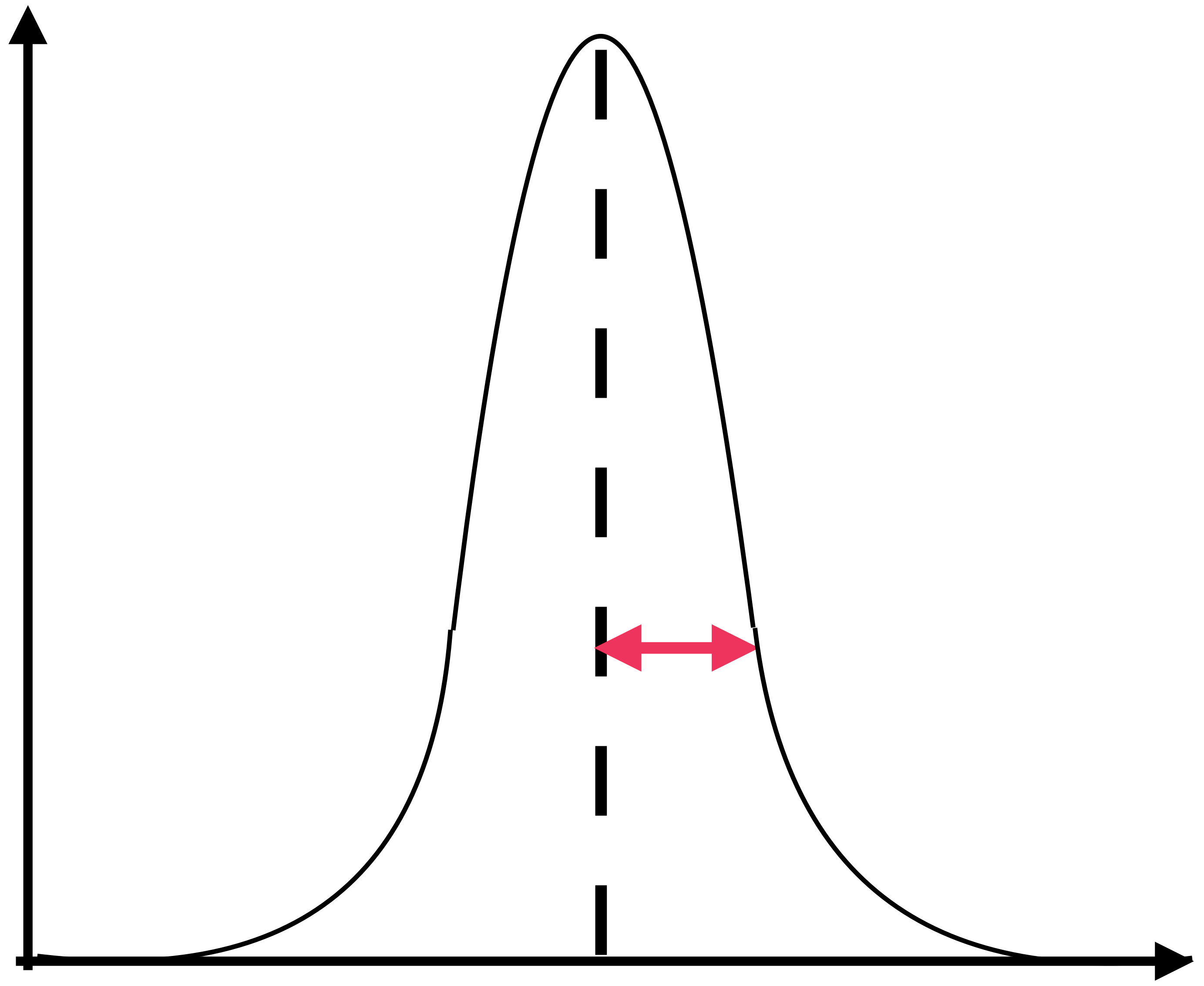




$\Delta p_T = p_T^{reco} - p_T^{true}$

- ML shows an improved performance over area-based method
- Similar performance for ML algorithms, use neutral network

ML approach: fragmentation bias

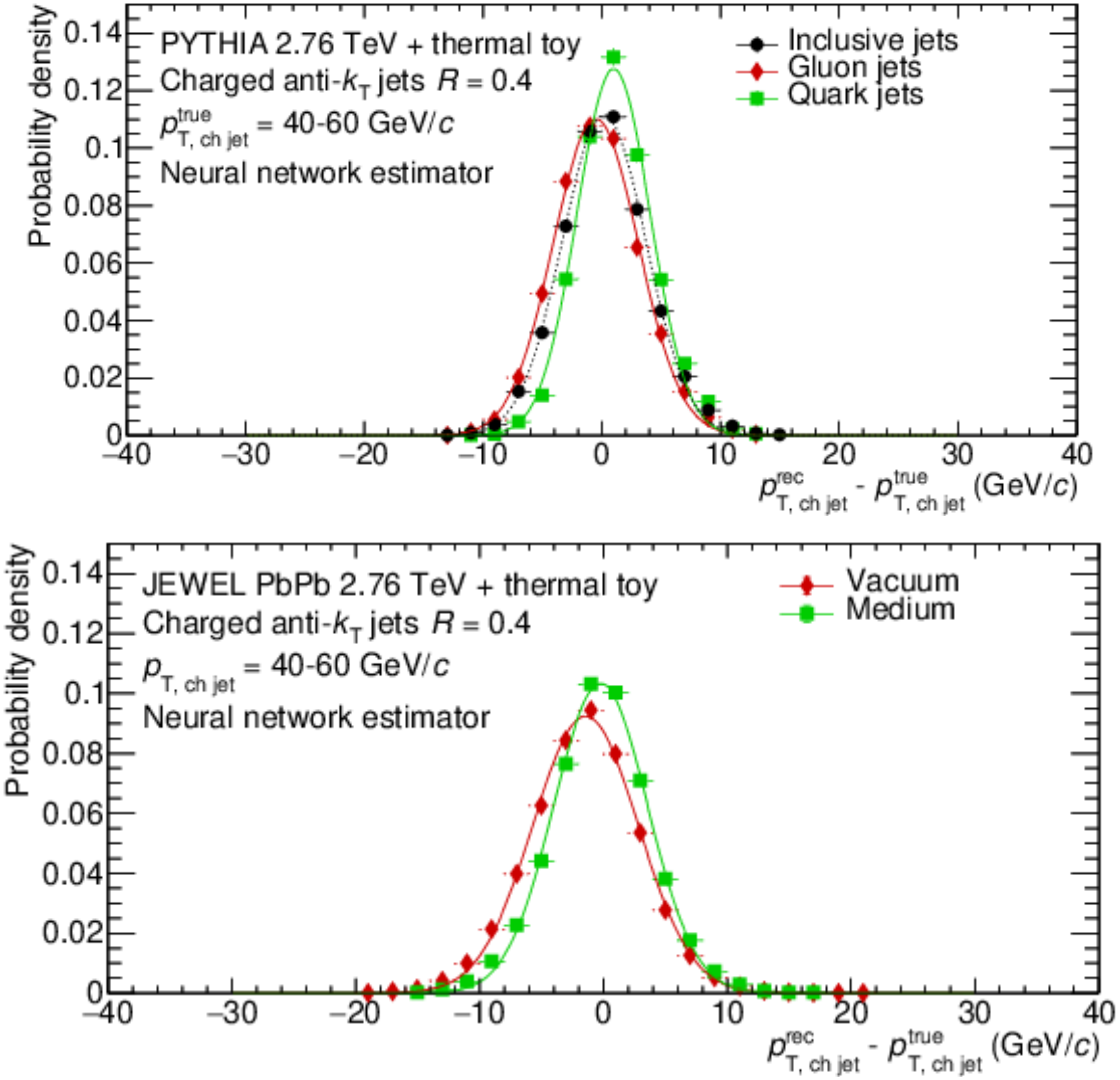
- Potential fragmentation bias due to using the jet constituents

➡ Estimate by looking quarks vs. gluons which have a different fragmentation pattern

➡ JEWEL is used to test bias to HI fragmentation which could be different than quark vs. gluon

- Small bias observed but many ongoing studies

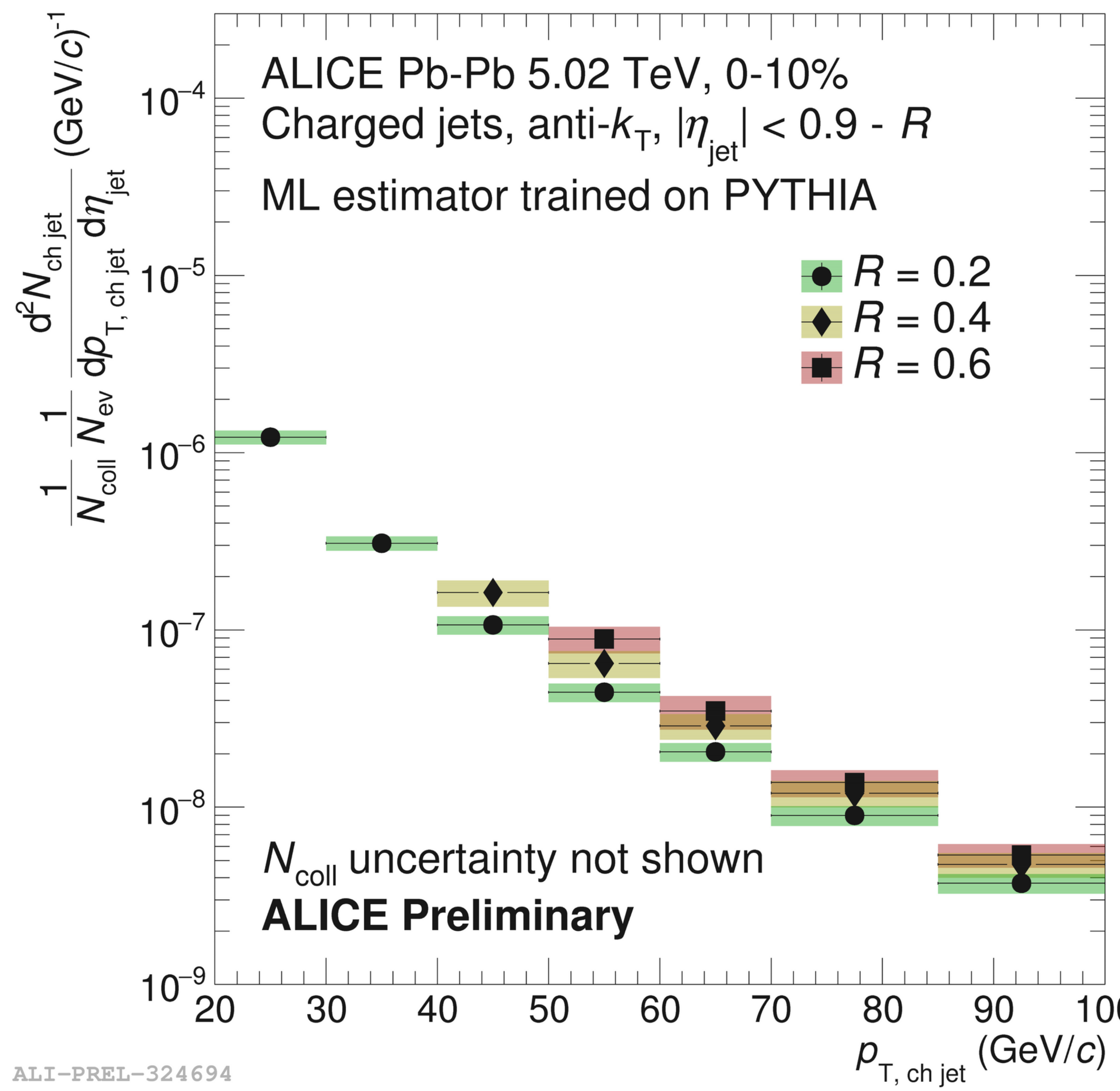
▸ Unfolding with response from quarks or gluons used as a systematic

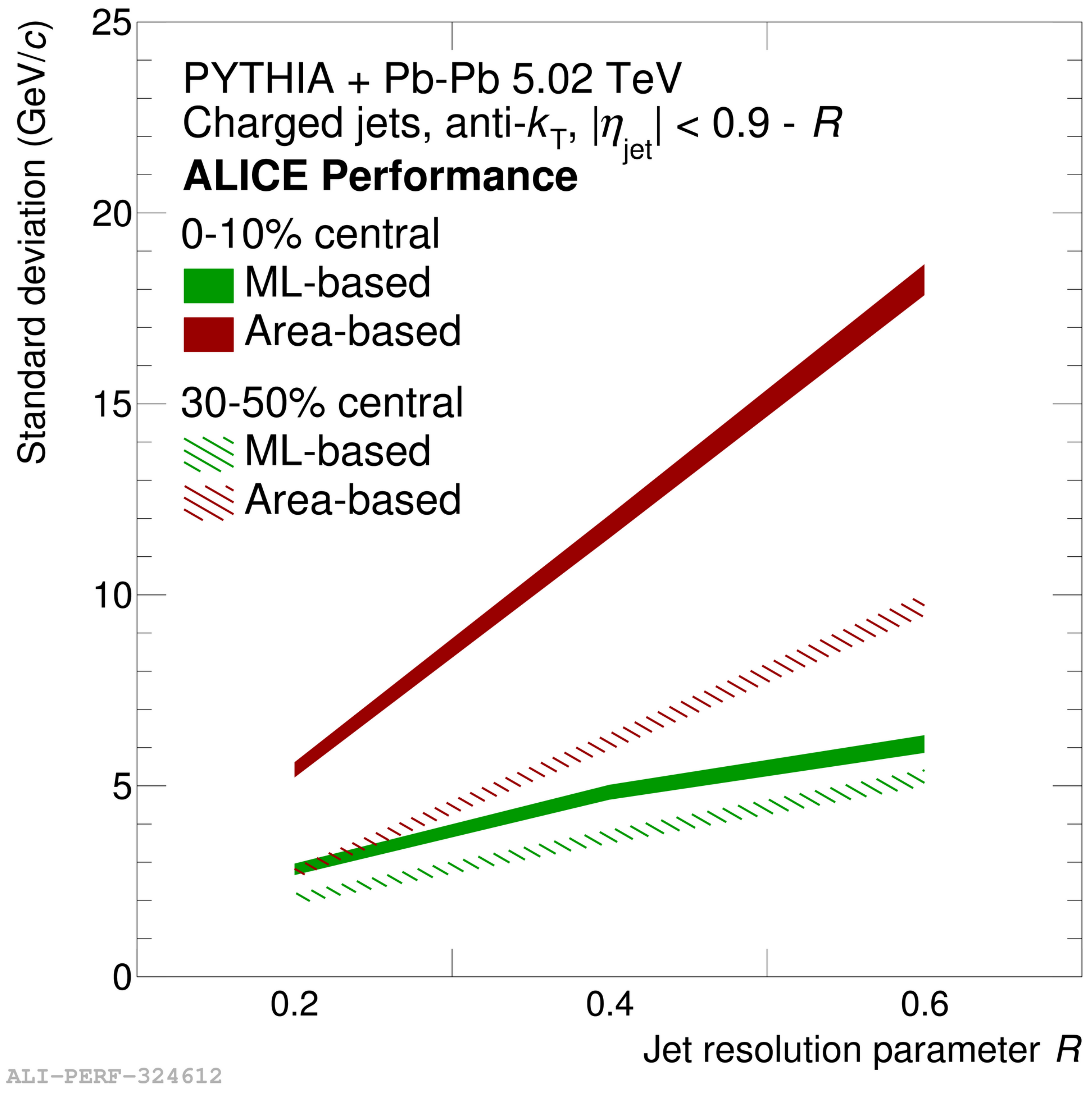


ML approach: apply to data

- ML method reduces fluctuations and improves resolution over area-based

➡ Extend to lower p_T and larger R (up to 0.6)





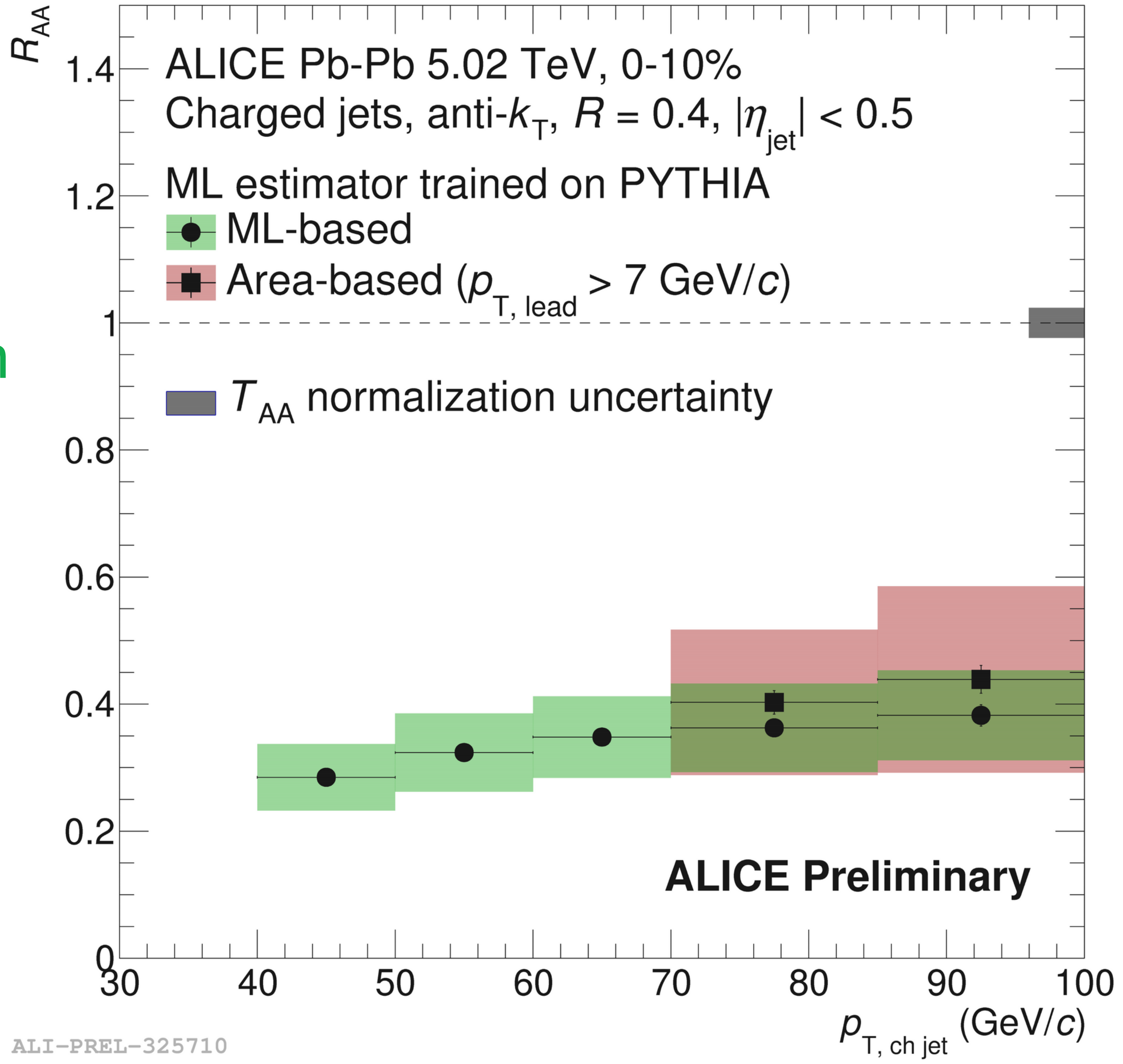
- Applied to ALICE 0-10% Pb-Pb data we see that going to larger R and lower p_T is experimentally possible

ML approach: R_{AA}

- Evaluate the R_{AA} in central collisions using the ML-based estimator and compare to the area-based method with a leading track bias (consistent!)

➡ See the p_T reach is much lower (down to 40 GeV) and the systematics are reduced!

$$R_{AA} = \frac{\frac{1}{N_{event}} \frac{d^2 N_{jet}^{PbPb}}{dp_T dy}\Big|_{cent}}{\langle T_{AA} \rangle_{cent} \times \frac{d^2\sigma_{jet}^{pp}}{dp_T dy}}$$



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  - ➡ R=0.6 is also possible down to 60 GeV
- Comparison to hybrid model!

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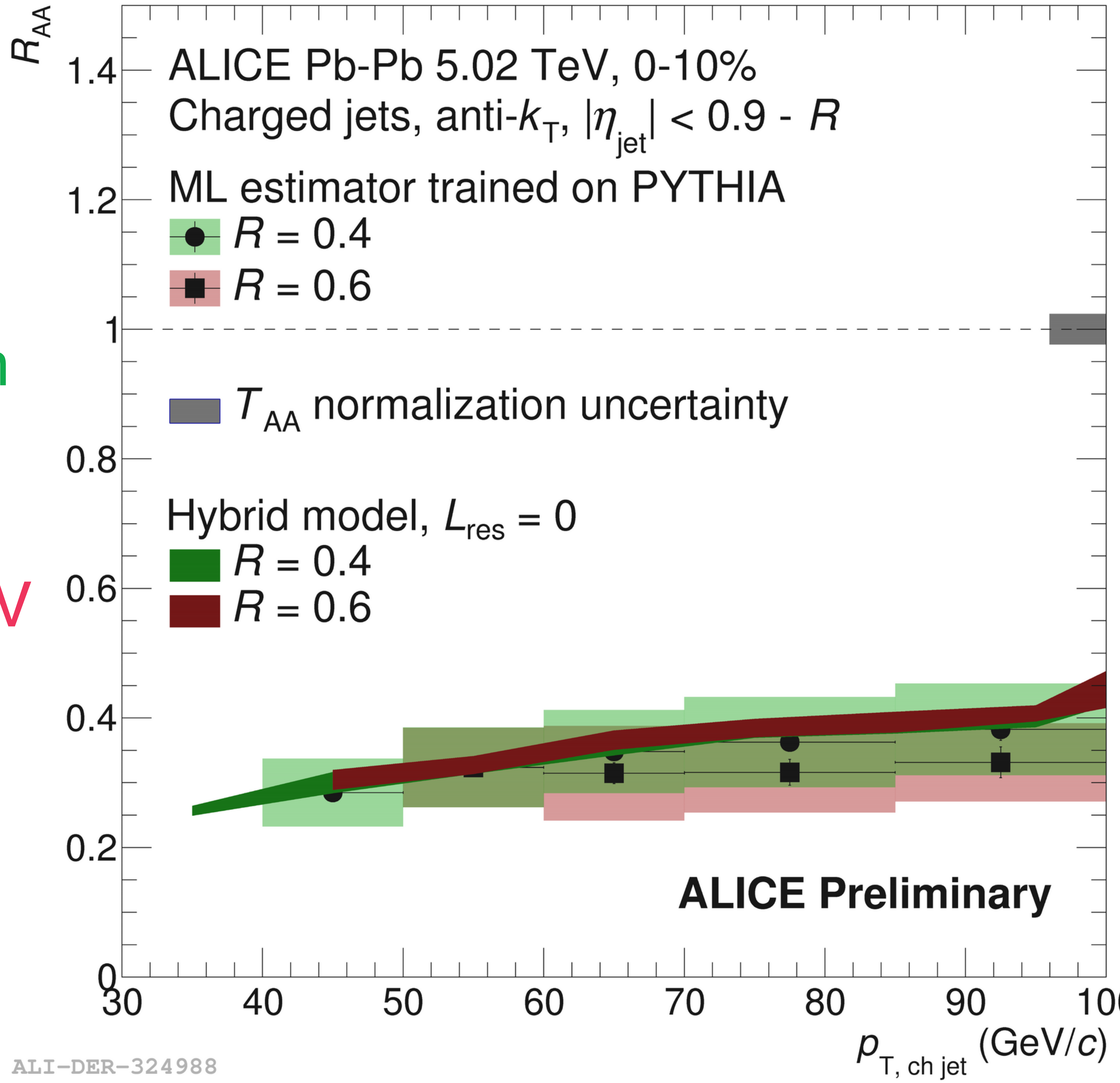
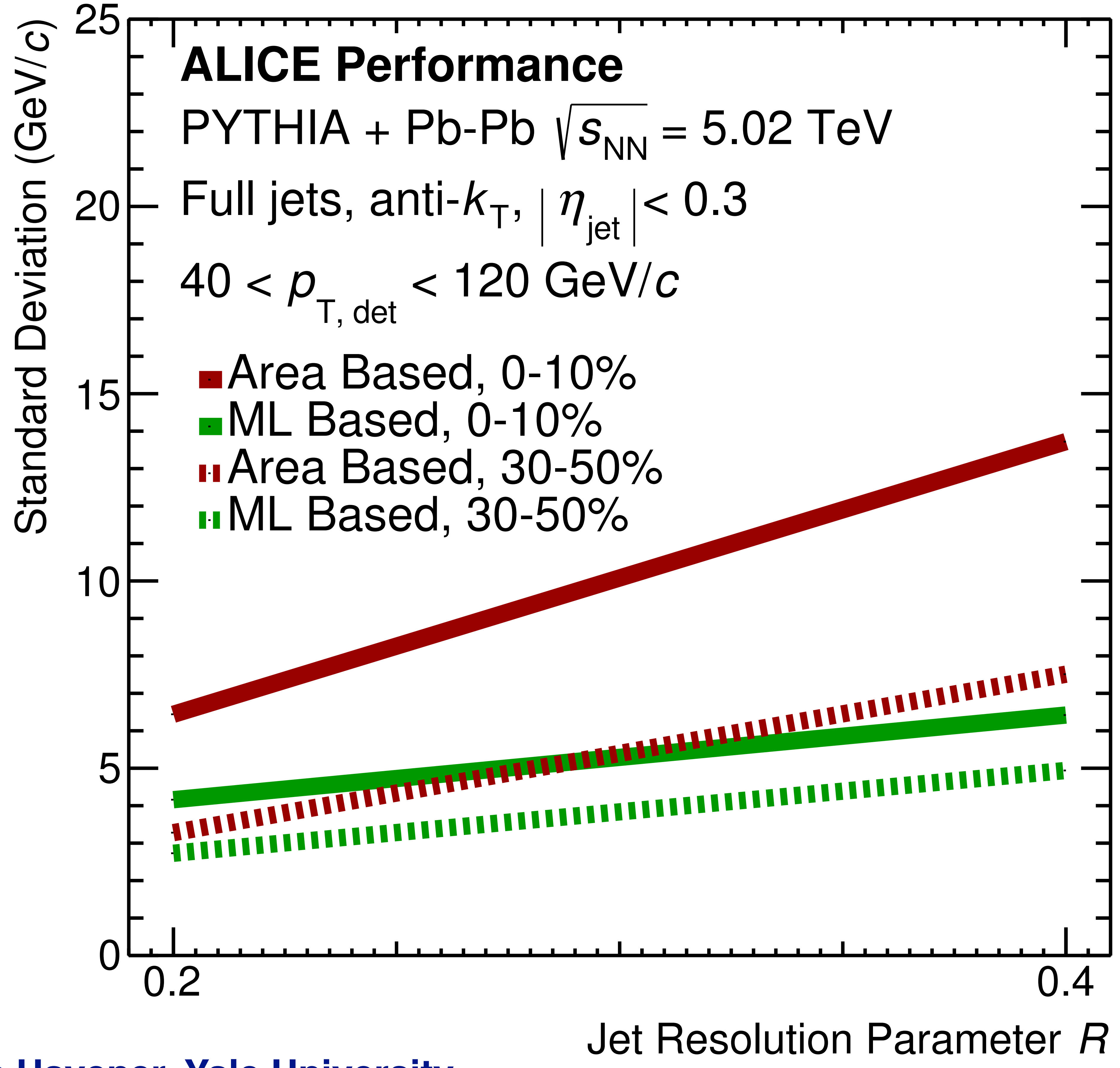
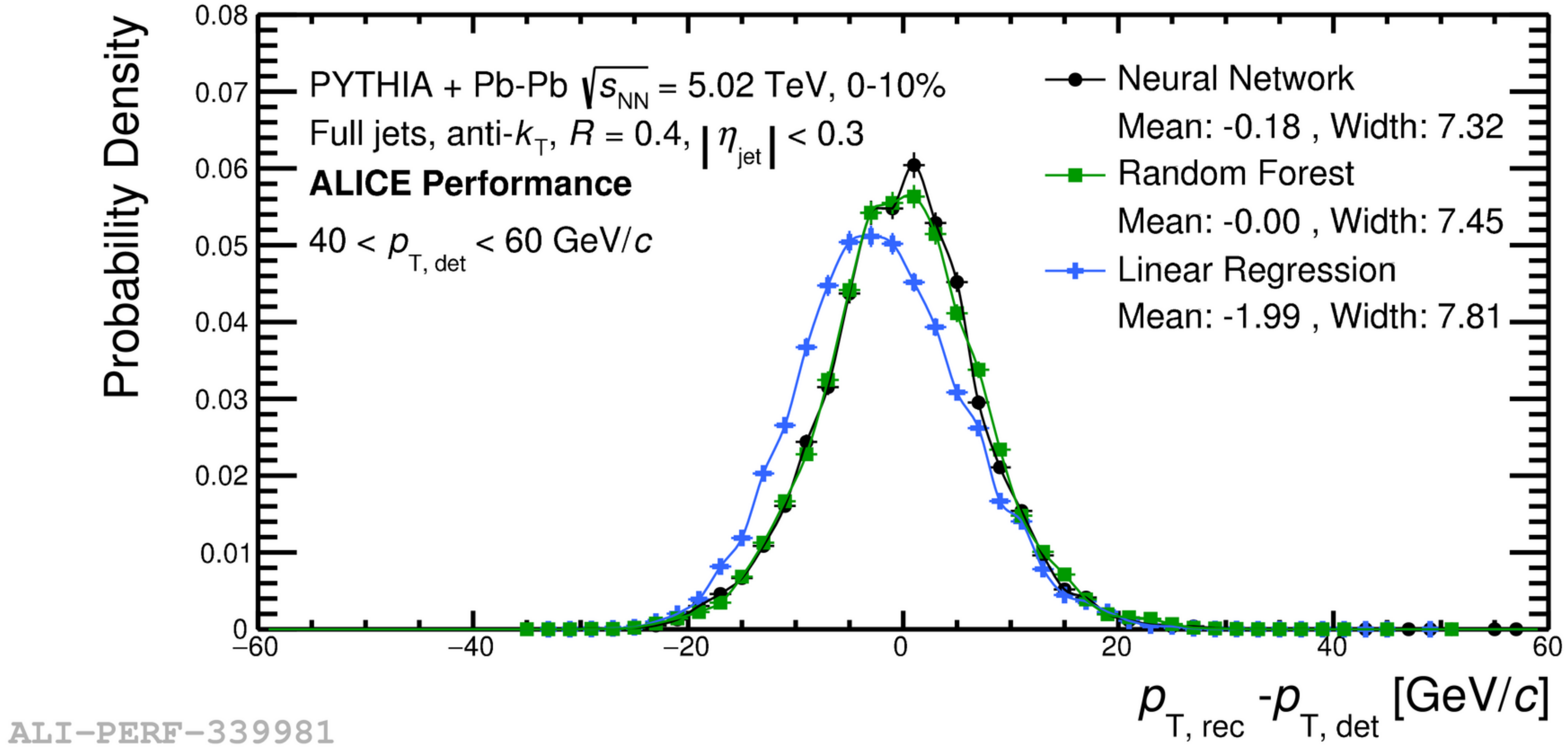


ML approach: full jets

- Extending method to full jets

➡ Full jets are closer to the theoretical definition of a jet





- Include neutral components as part of input now
- See similar improvement as charged jets!
- Next step: apply to data

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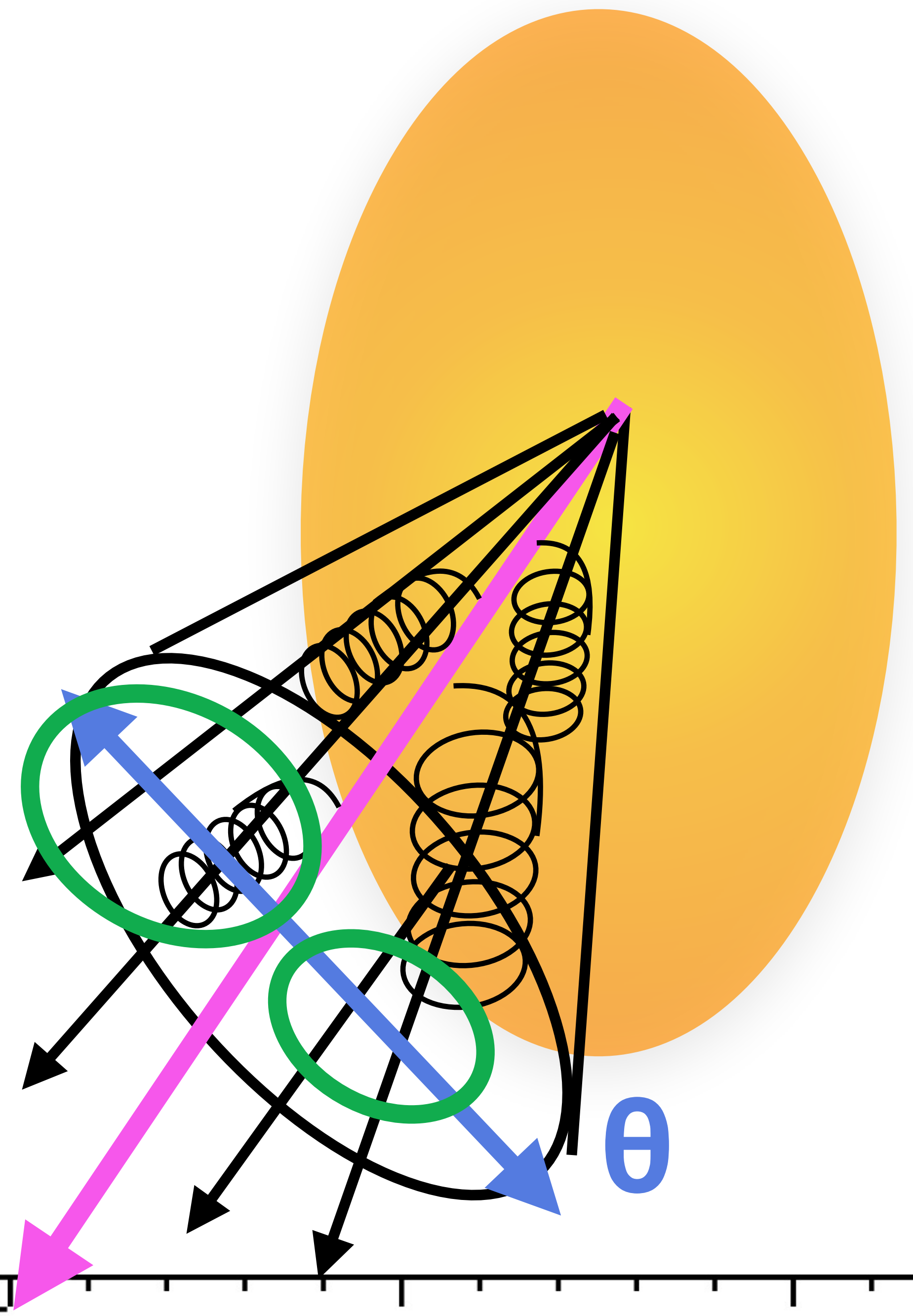
Jet substructure

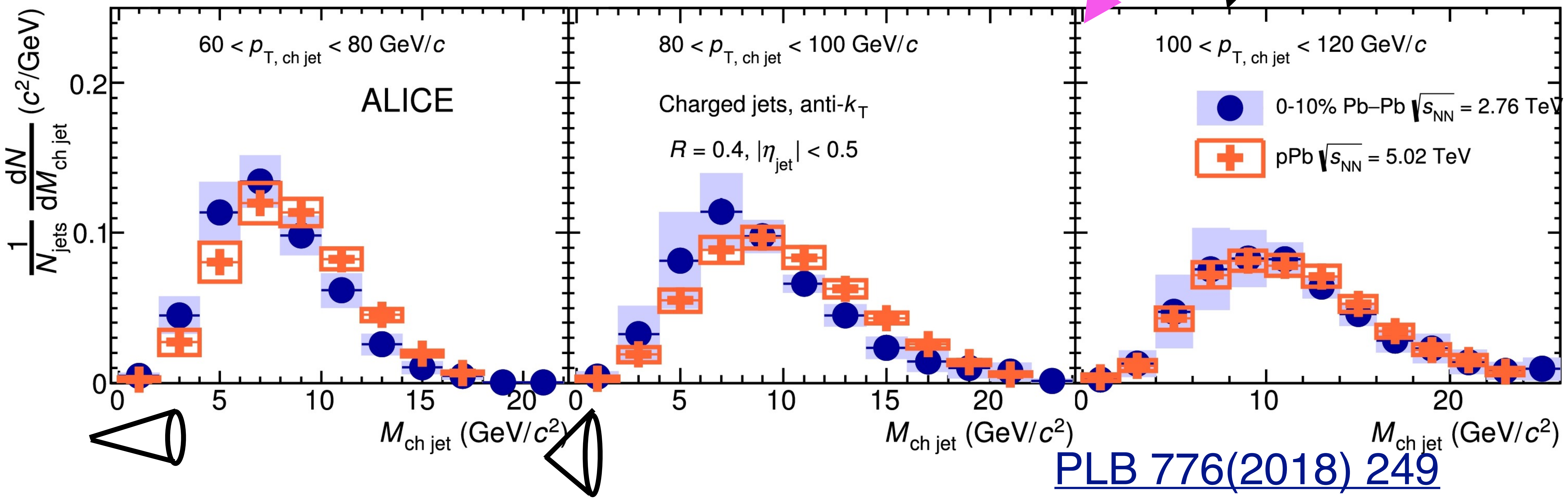


- Jet internal structure is expected to be modified by the medium produced in HI collisions

➡ Learn more about the medium by studying jet substructure!

- Intuition to look at jet mass but this proves to be insensitive to medium effects

- Many measurements of novel jet substructure tools using jet splittings



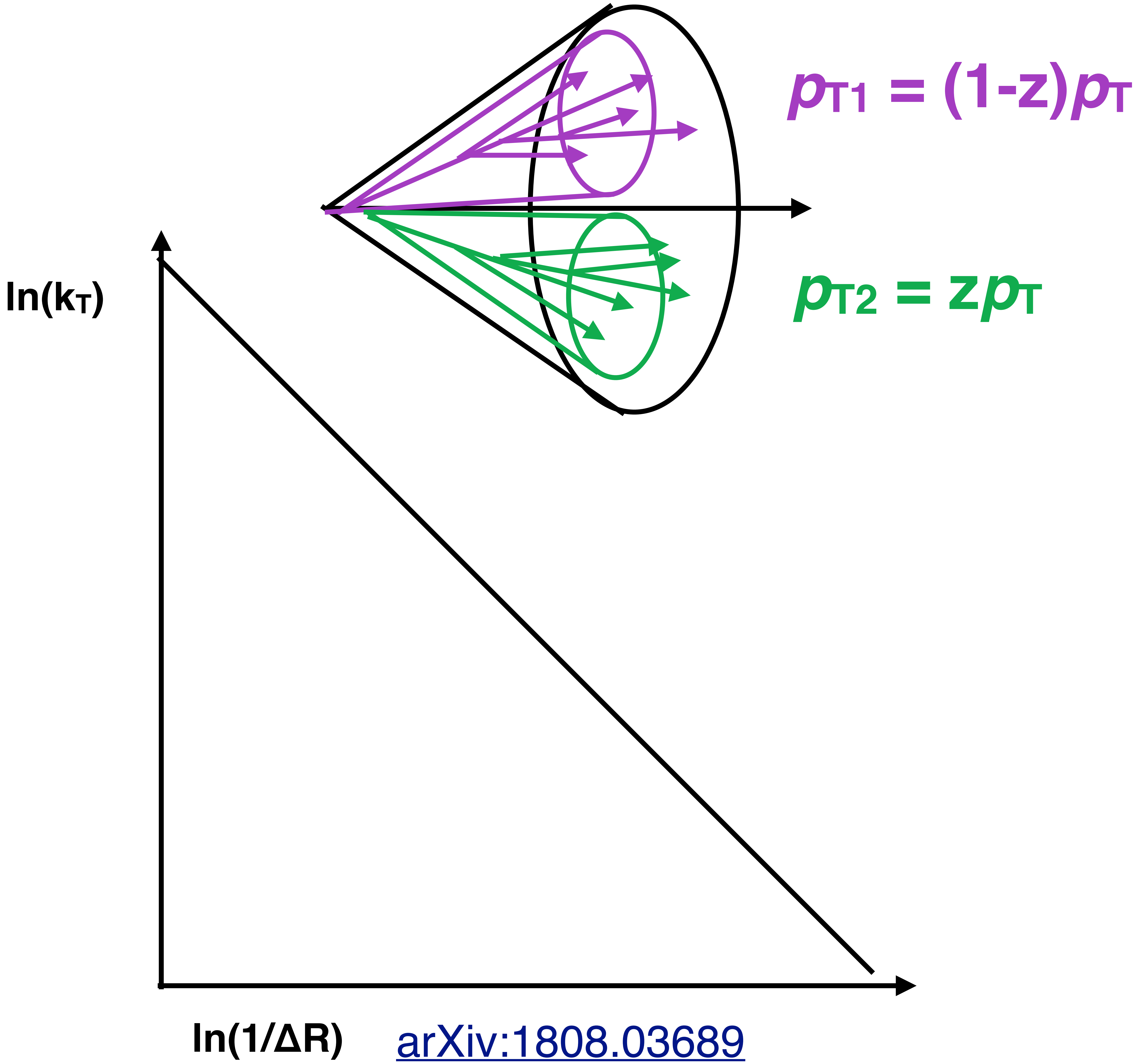
PLB 776(2018) 249

‣ Before measuring jet substructure the background removal needs to remove the background for the jet constituents instead of the jet as a whole

Exploring the Lund Plane: in vacuum

- Lund Diagram*: phase space of jet splitting

*Z. Phys. C43 (1989)
JHEP 12 (2018)



arXiv:1808.03689

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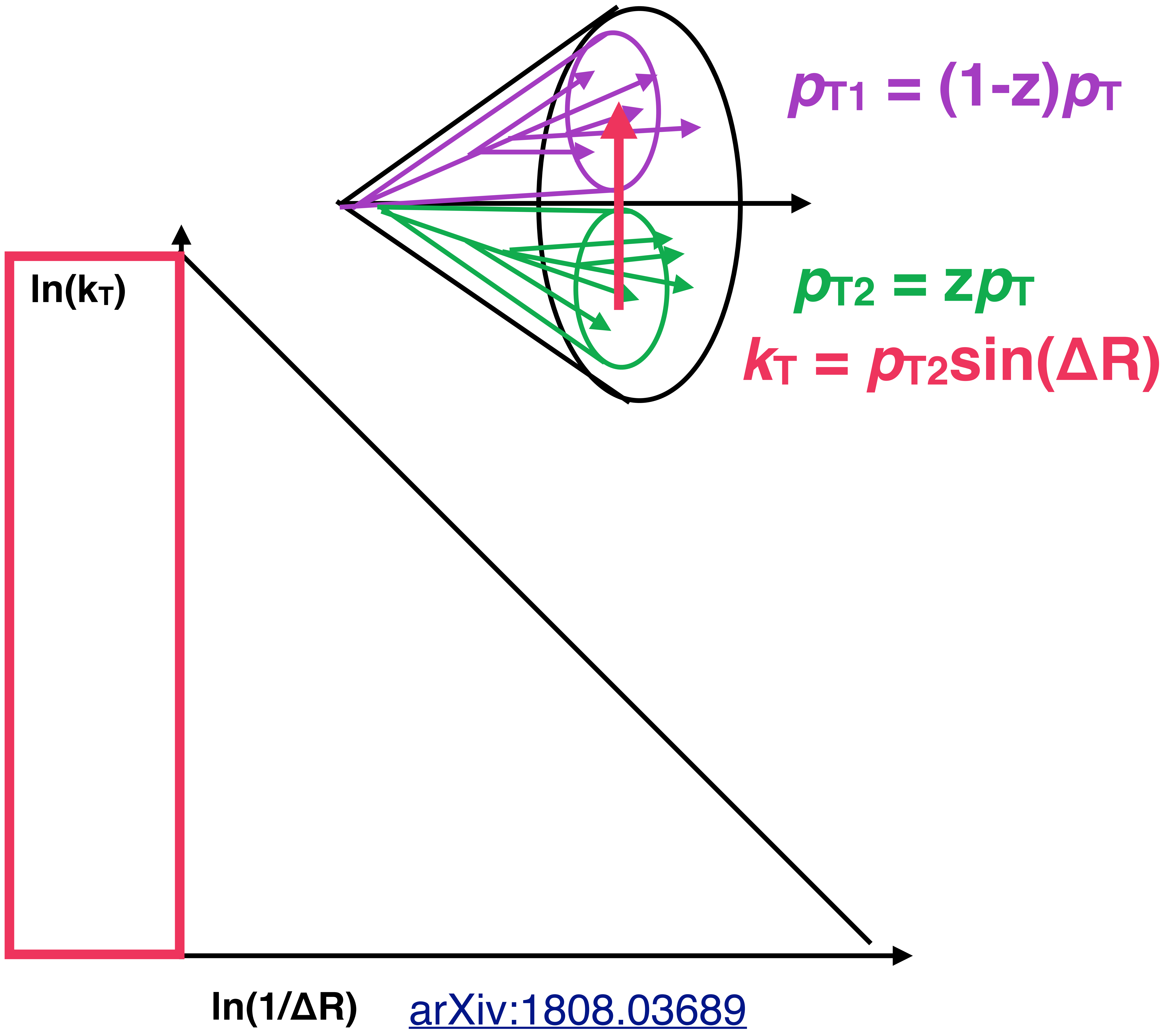

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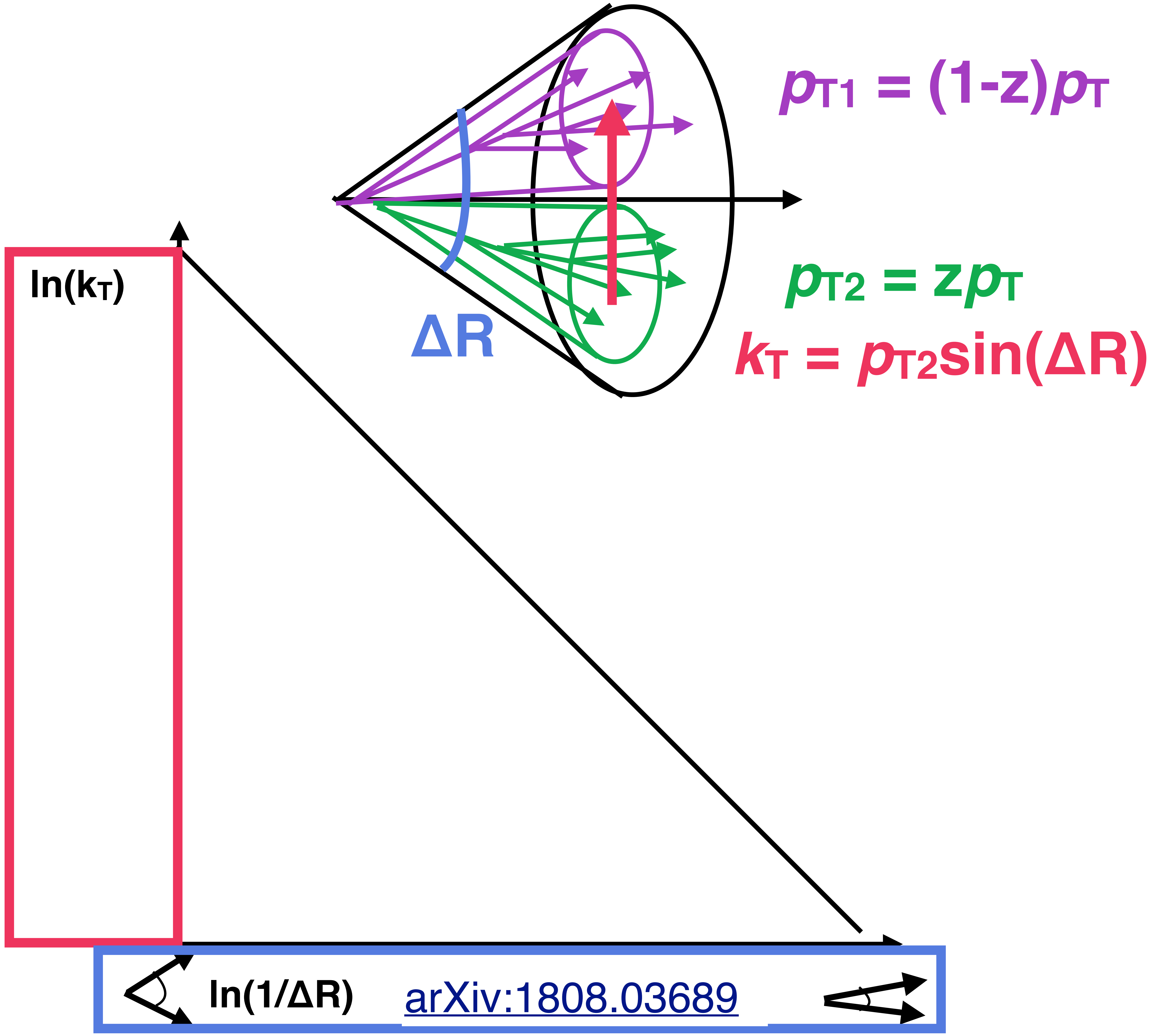
- ΔR: opening angle between subjets



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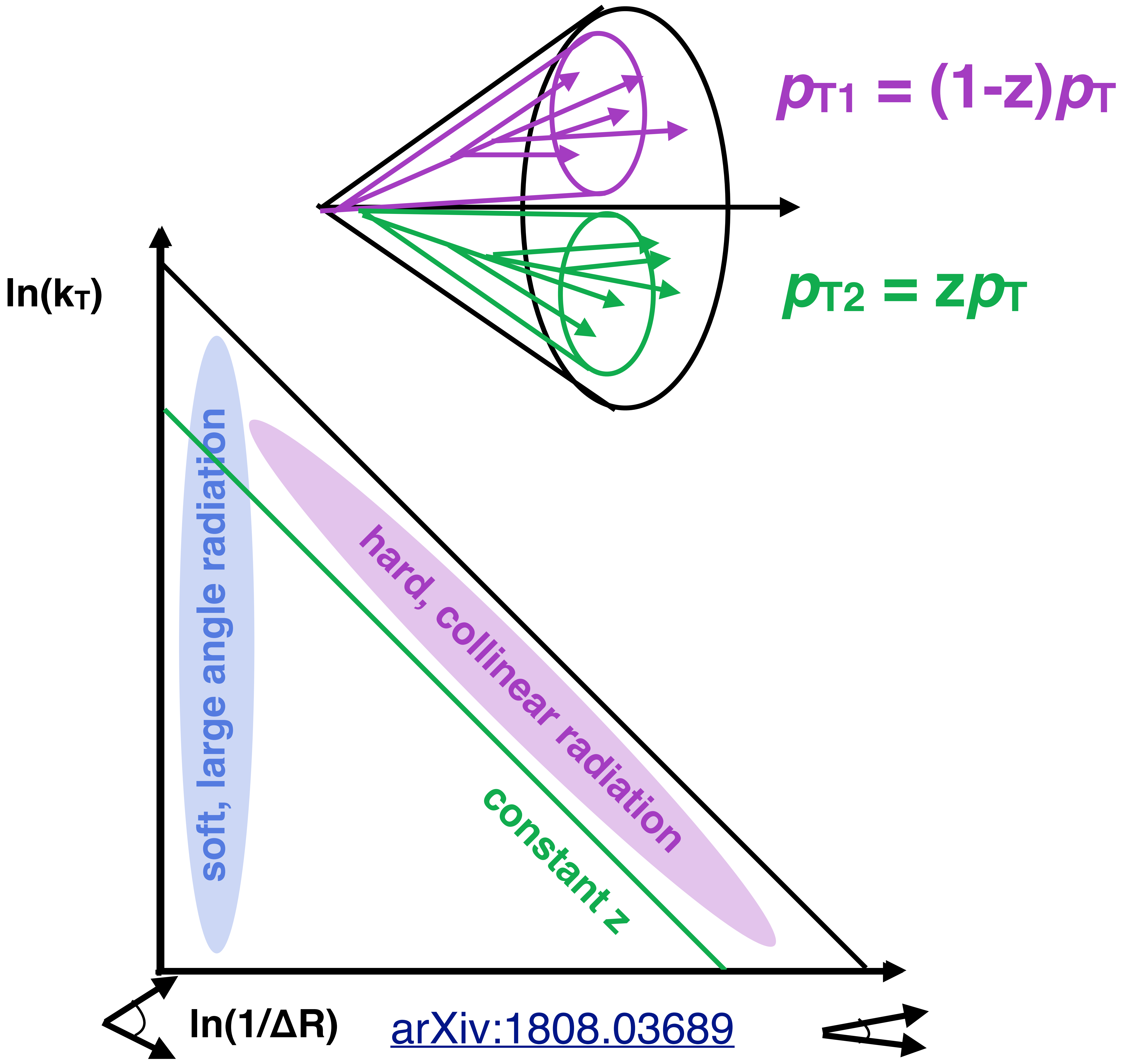

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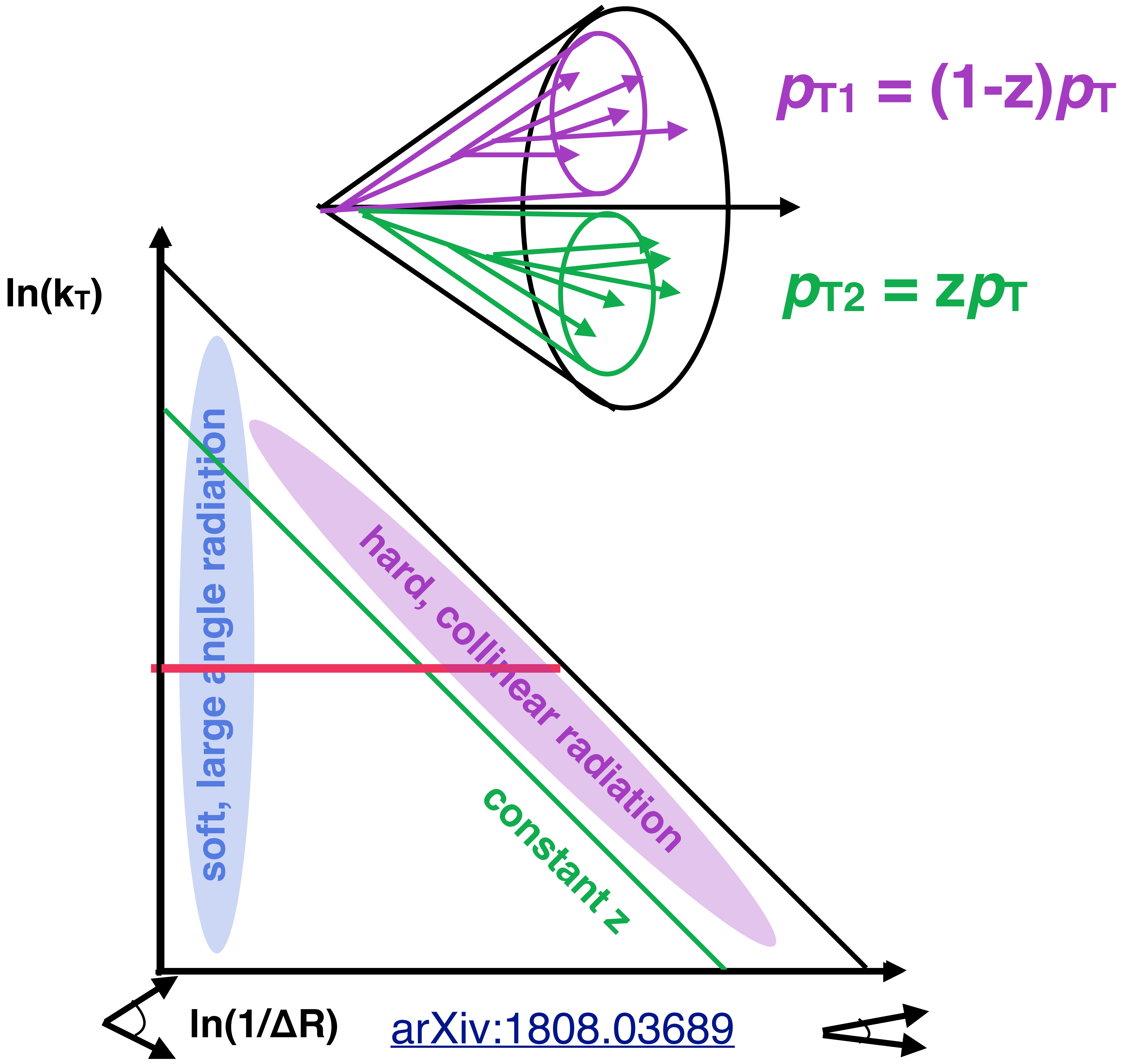

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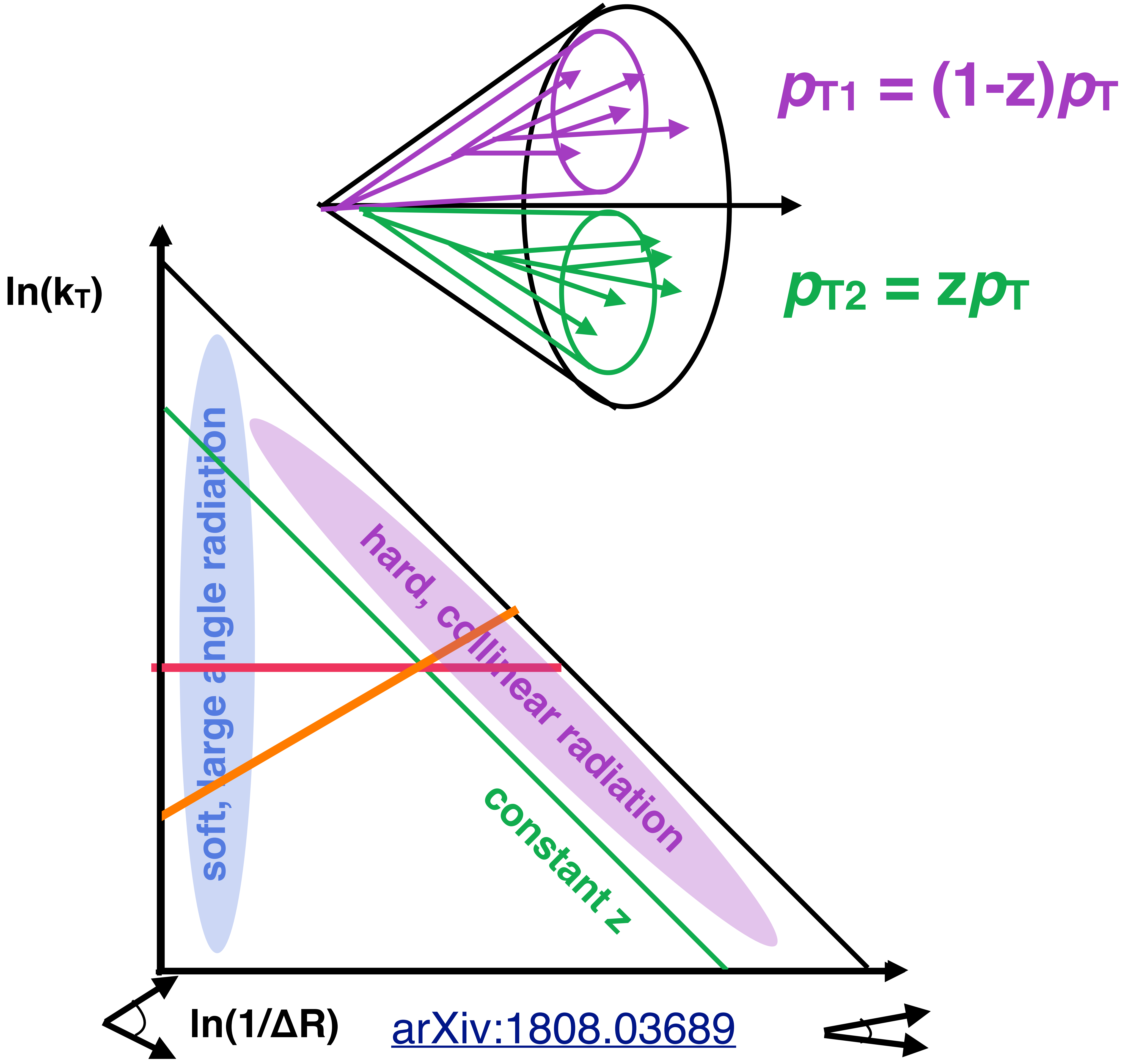
- Formation time: how long until the splitting occurred

$$t_f = \frac{1}{(1-z)k_T\Delta R}$$

Y. L. Dokshitzer, et.al.



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Exploring the Lund Plane: in medium

- Jet splittings in heavy-ion (HI) collisions

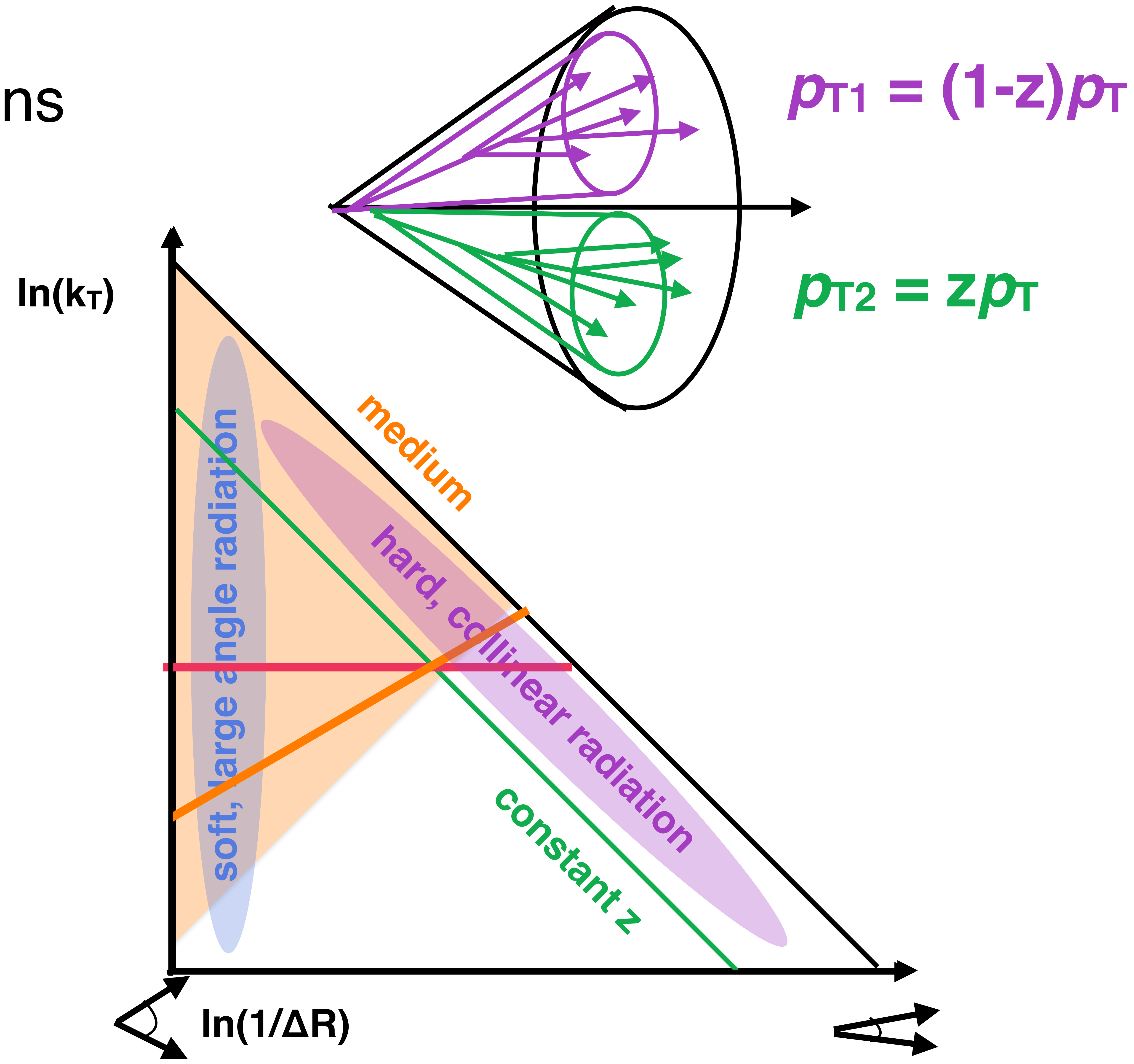
➡ in/out of medium splittings

- ▸ Earlier/wider splittings experience more medium

➡ Vacuum splittings vs. non-perturbative in-medium splittings

➡ Coherence vs. decoherence

- ▸ Split jets should be more quenched



Soft drop grooming

- Reconstruct anti-k_T R=0.4 charged jets between 80-120 GeV/c with jet-by-jet constituent background subtraction* (in HI collisions)

*JHEP 06 (2014) 092

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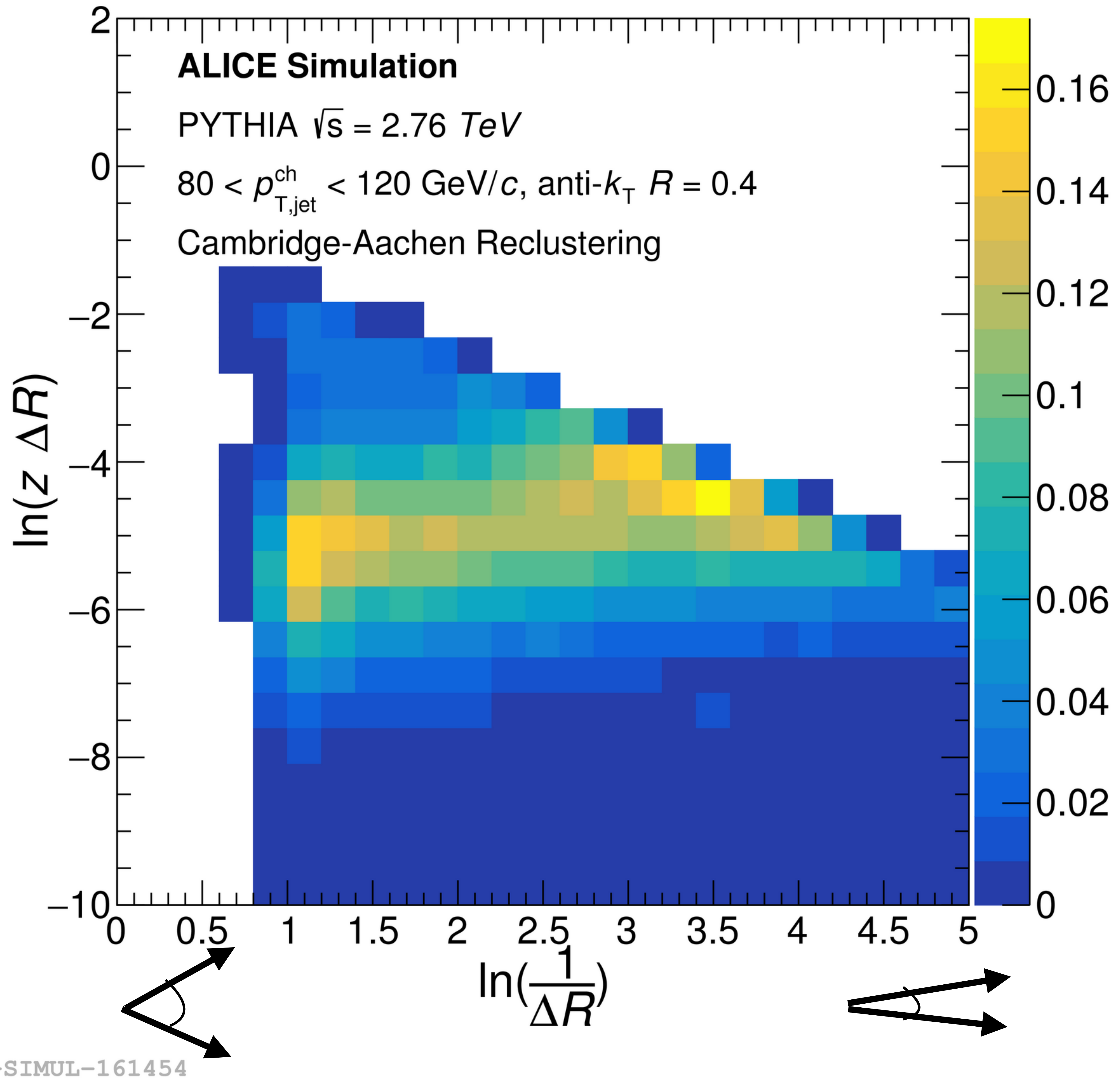

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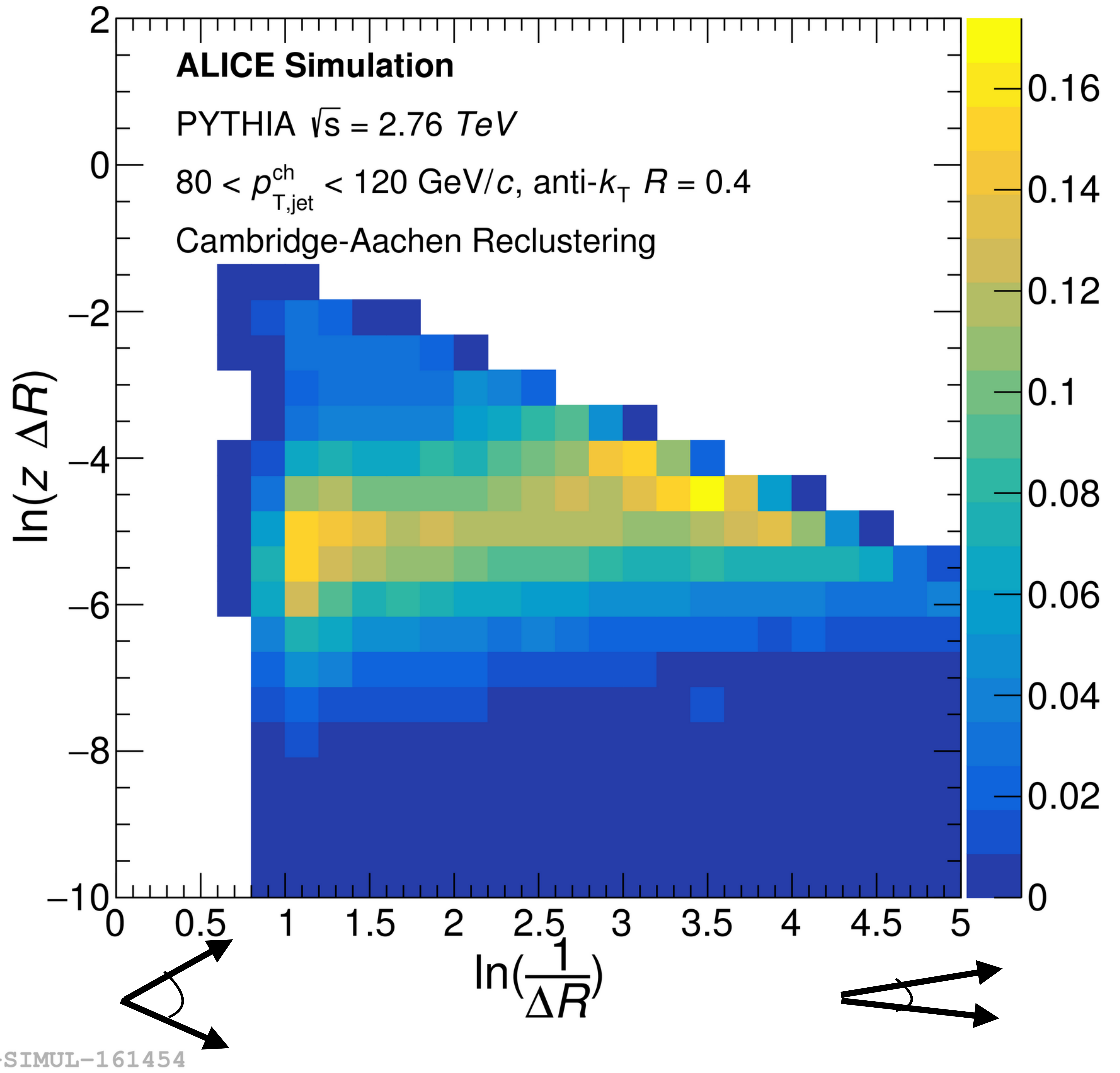
$$z_g > z_{cut}\theta^\beta \qquad \theta = \frac{\Delta R}{R}$$



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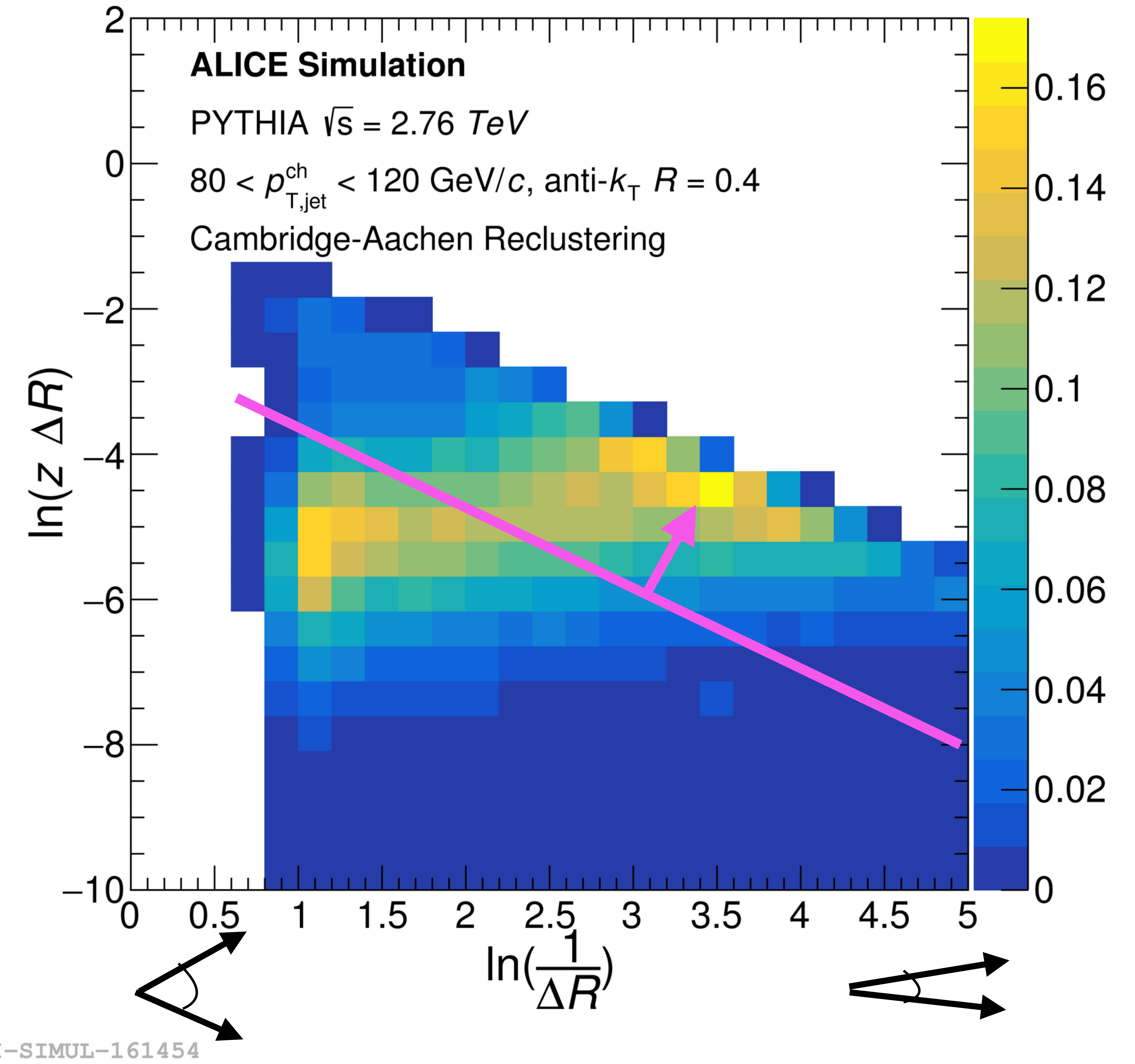
- Soft drop grooming to access hard splitting

$$z_g > z_{cut}\theta^{\beta} \qquad \theta = \frac{\Delta R}{R}$$

- Default condition: $z_{cut} = 0.1$, $\beta = 0$

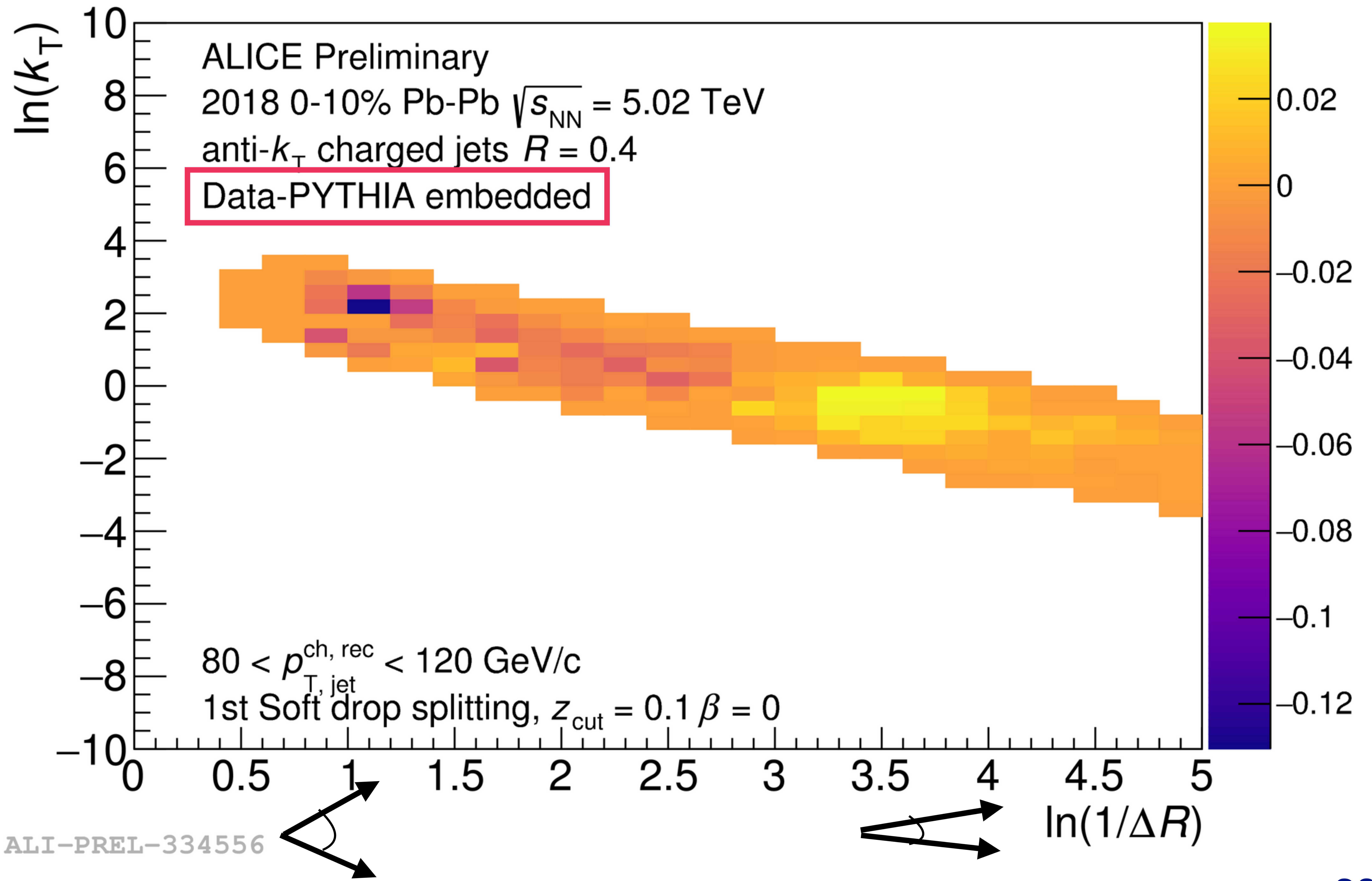


Exploring the Lund Plane in Data

New 2018 0-10% Pb-Pb collision data at 5.02 TeV

- Compare to PYTHIA8 embedded into real 0-10% Pb-Pb collisions

- Subtract the embedded MC from the data in order to remove the effects from the large HI background



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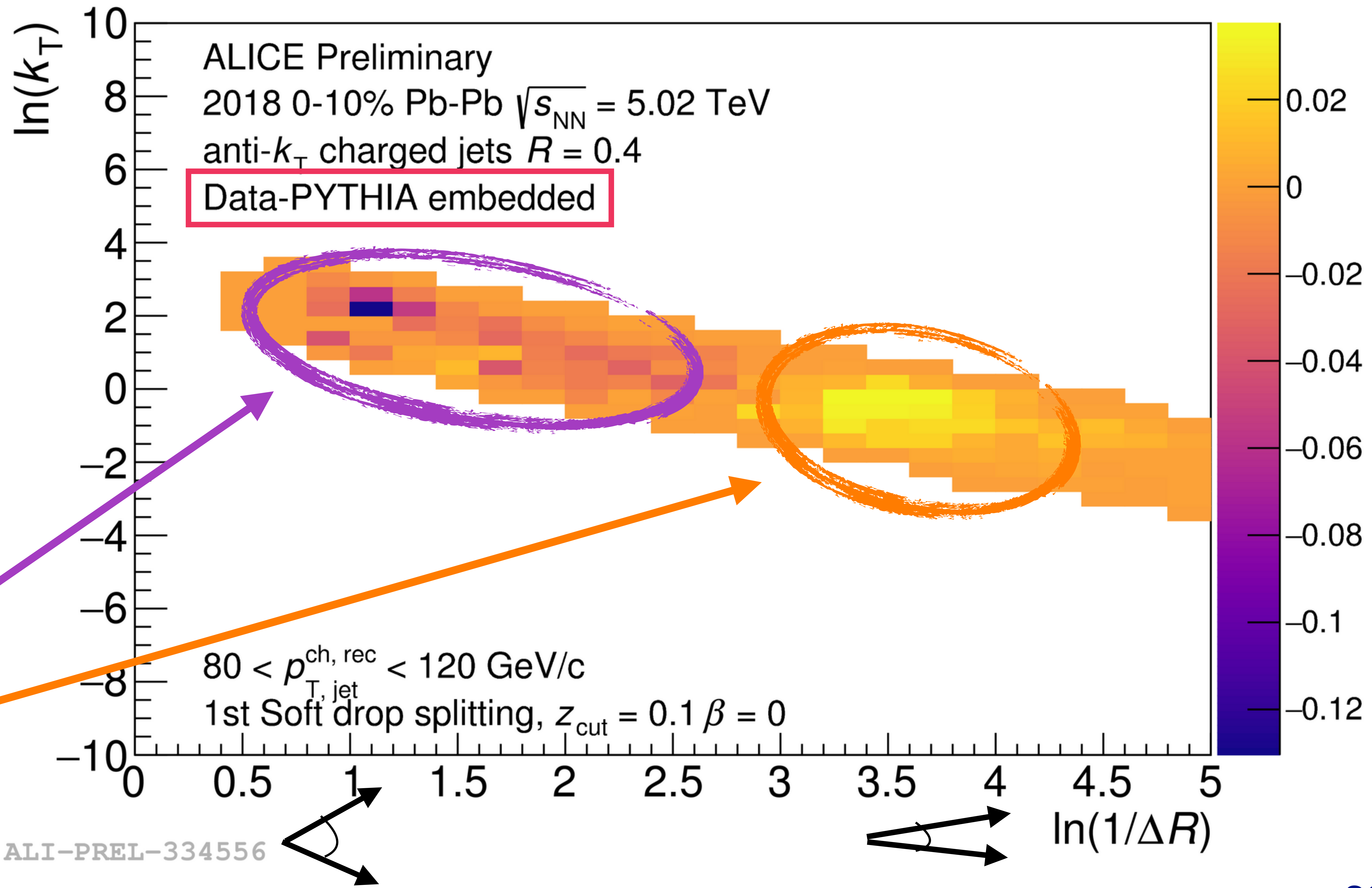
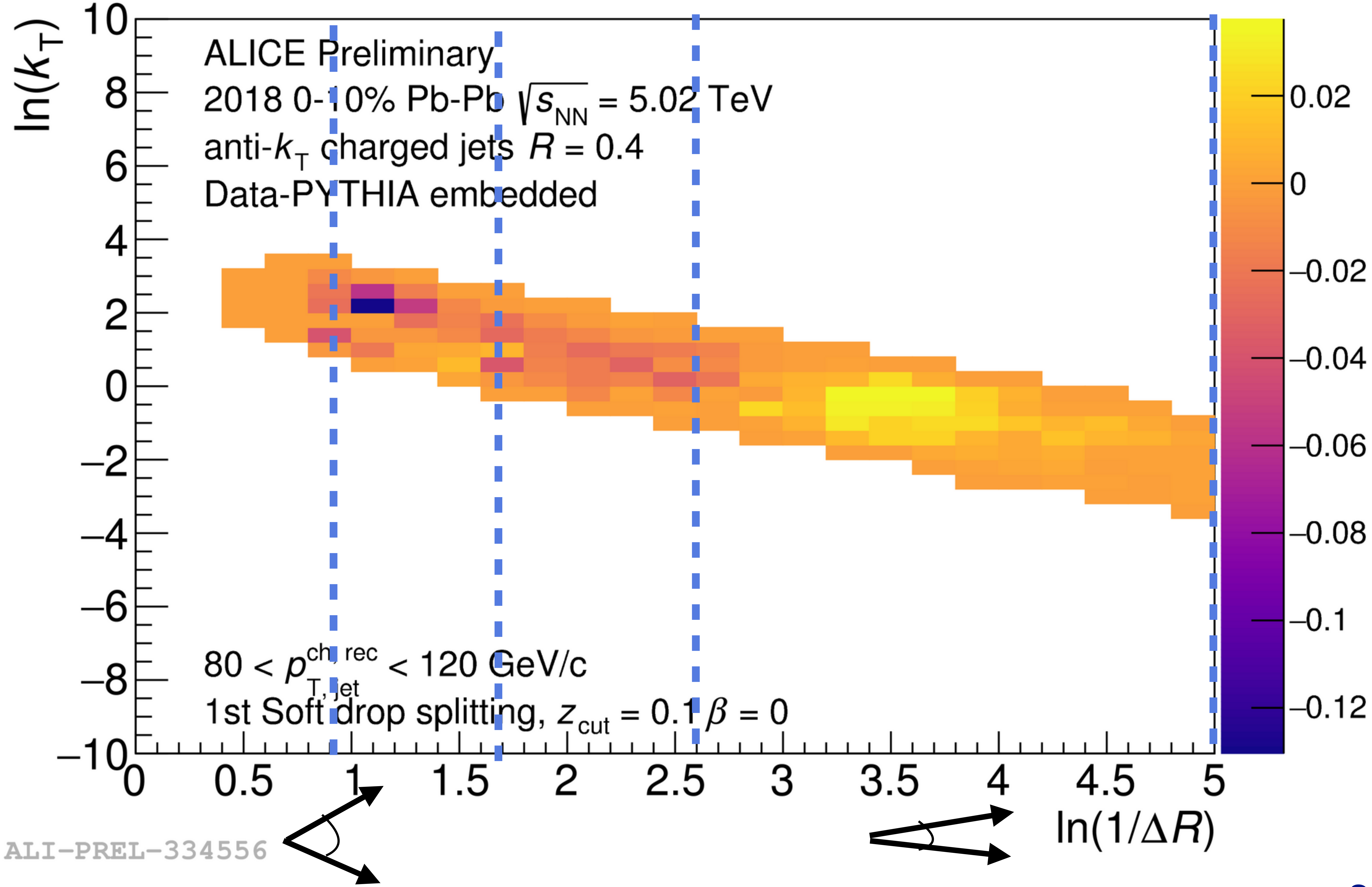
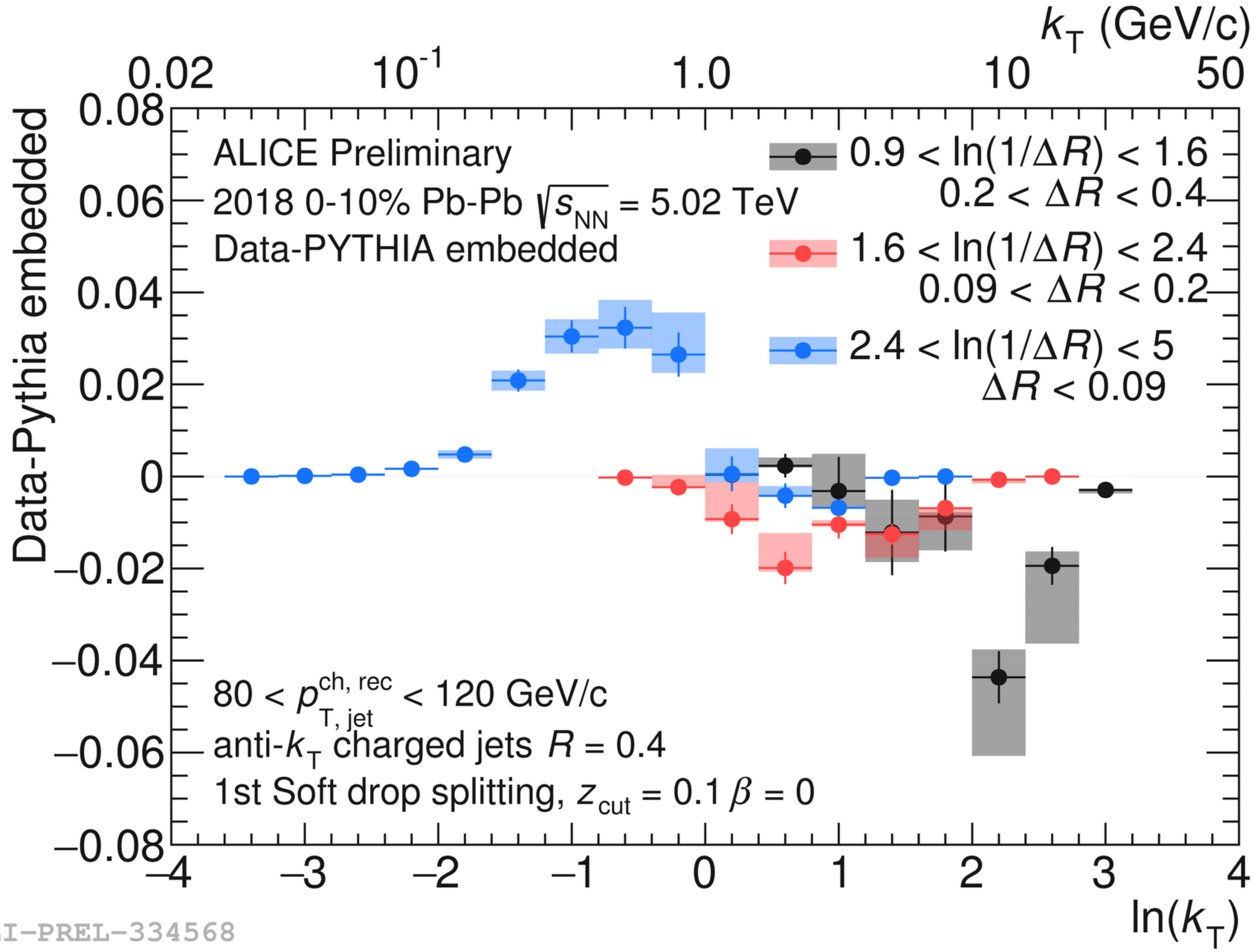


Exploring the Lund Plane in Data

- Next: look at projections onto the splitting scale (k_T) in ΔR bins



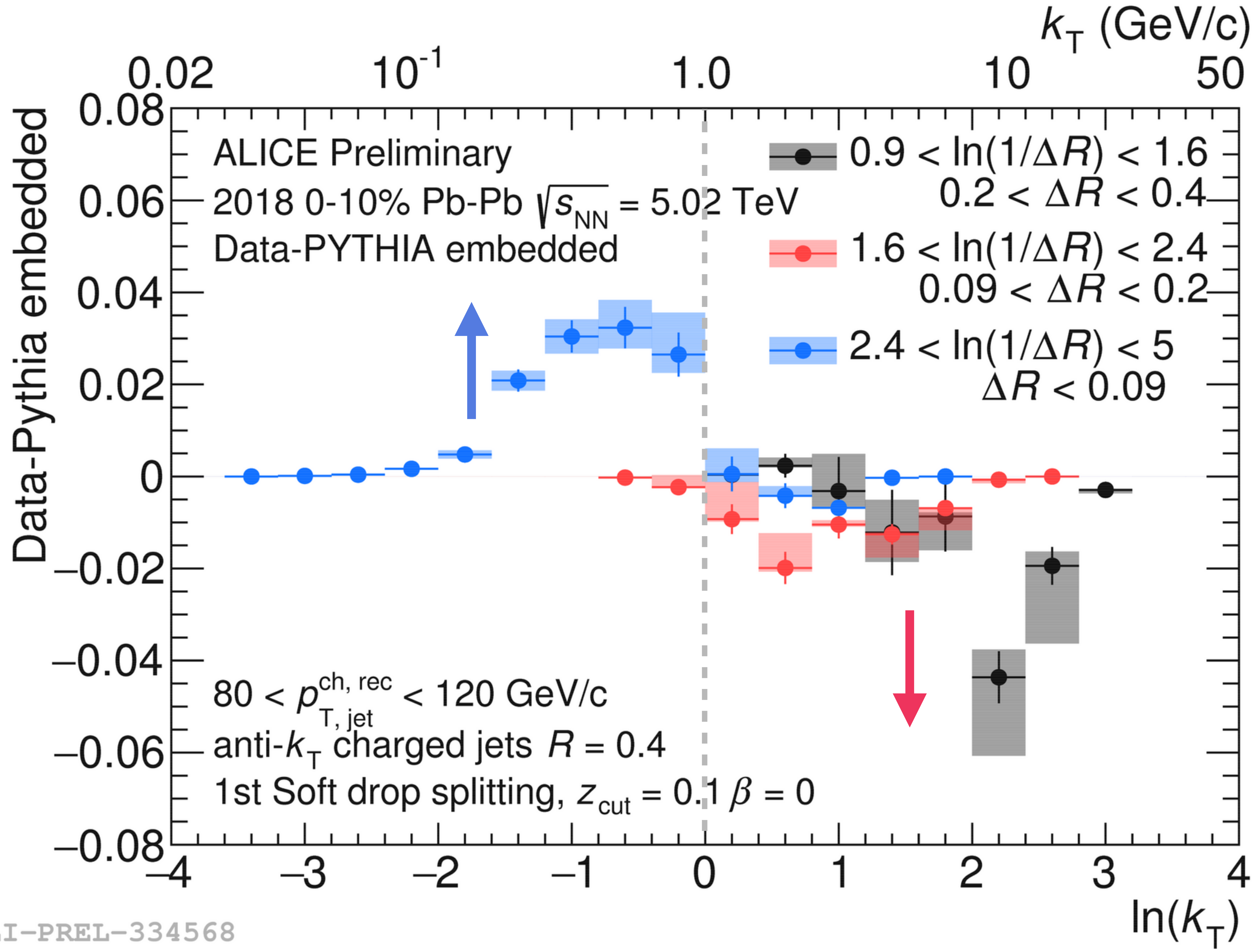
Lund Plane Projections



Lund Plane Projections

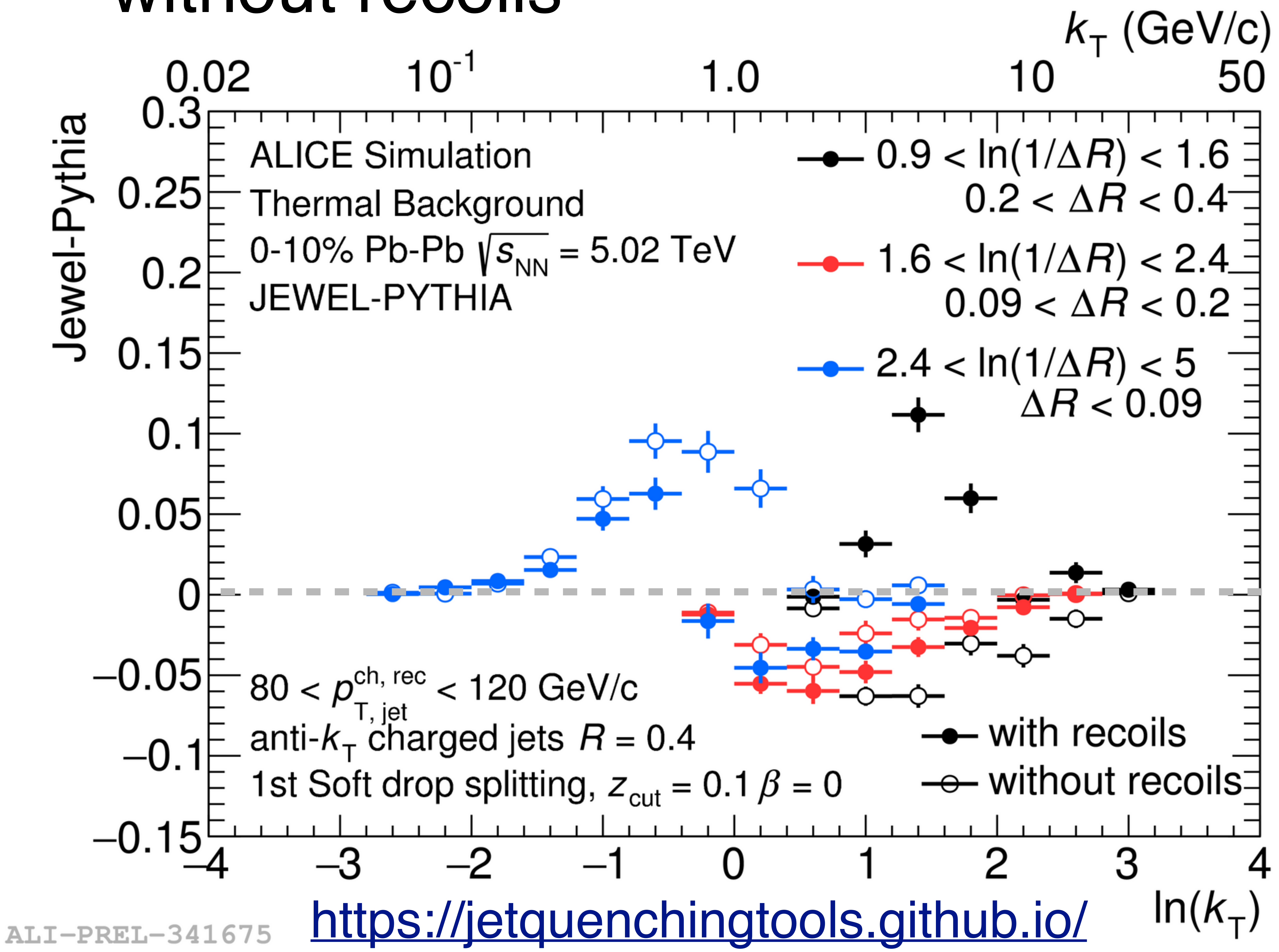
- Suppression at large ΔR and enhancement at small ΔR

- Consistent with idea the large angle splittings see more of the medium and are suppressed

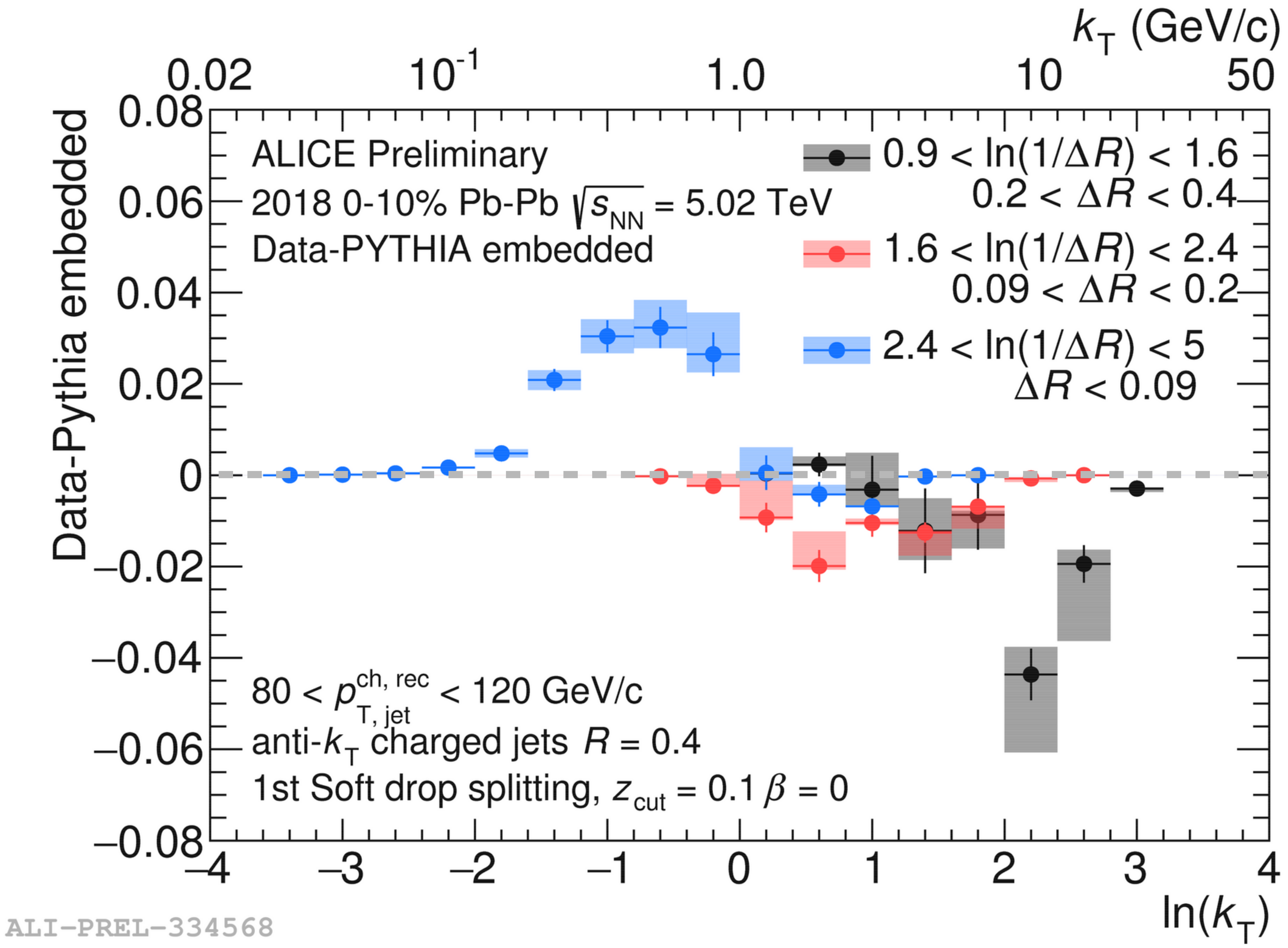


Lund Plane Projections

- Compare to JEWEL-PYTHIA embedded in a thermal background with and without recoils



https://jetquenchingtools.github.io/



Lund Plane Projections

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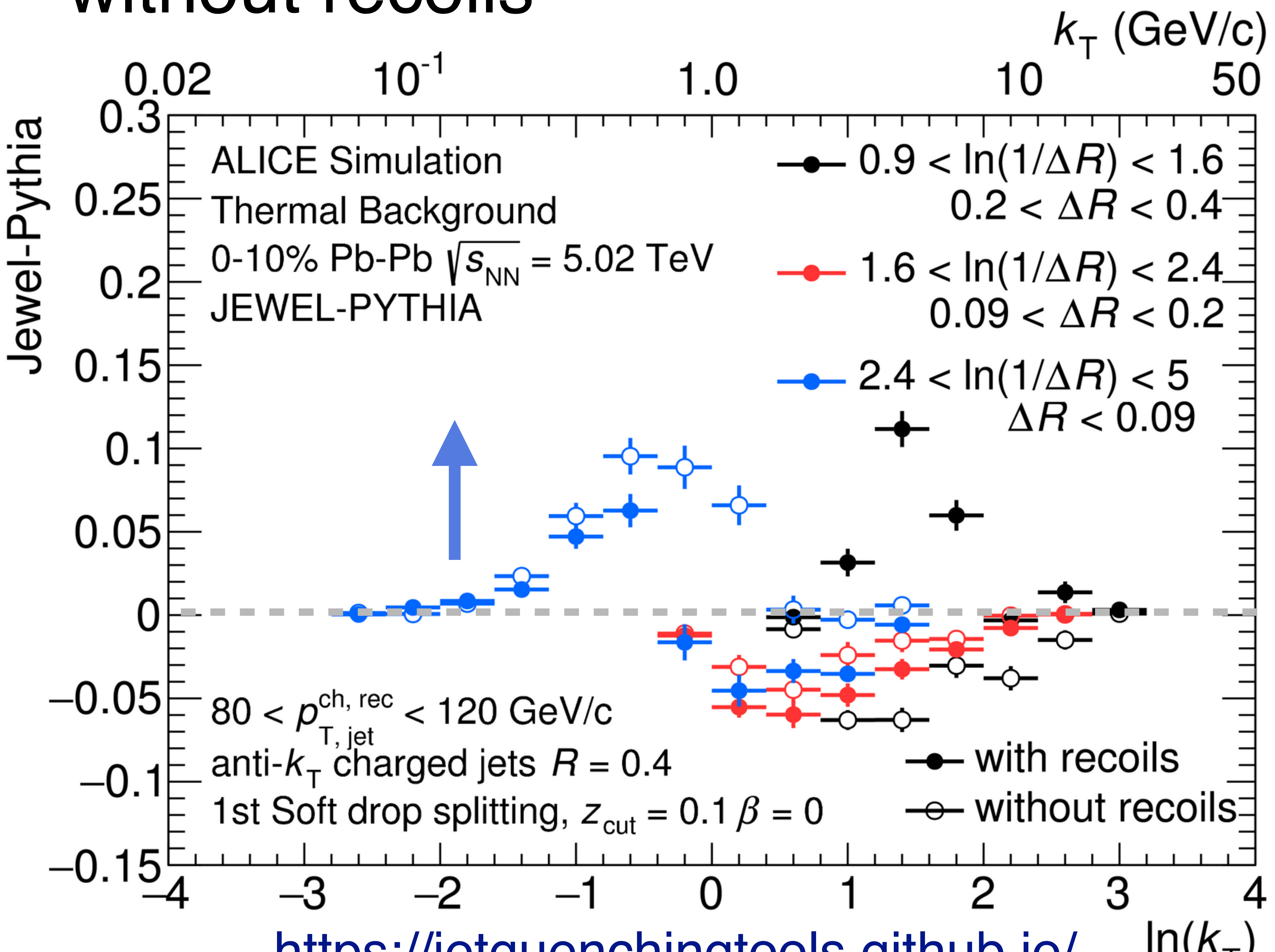

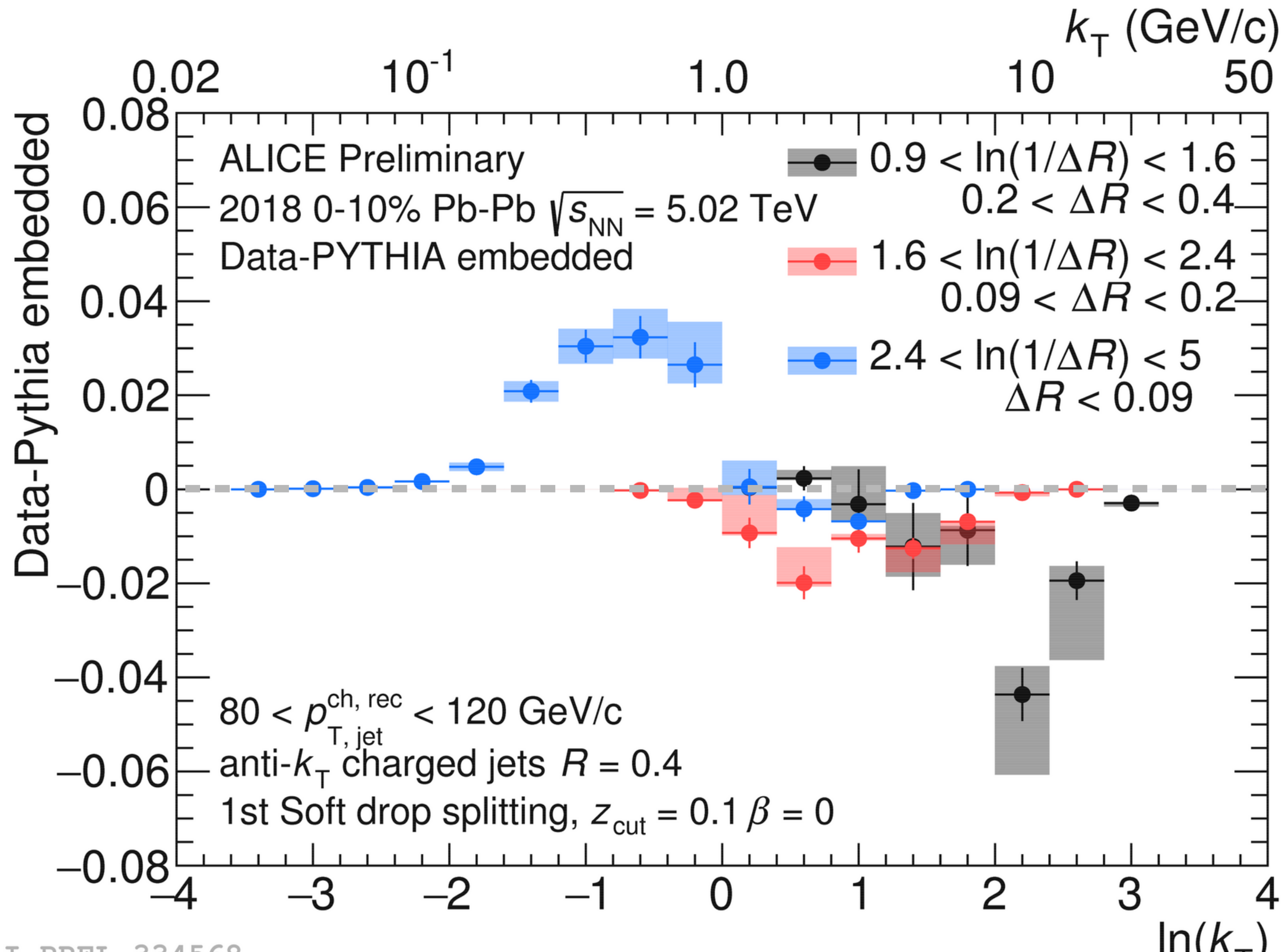

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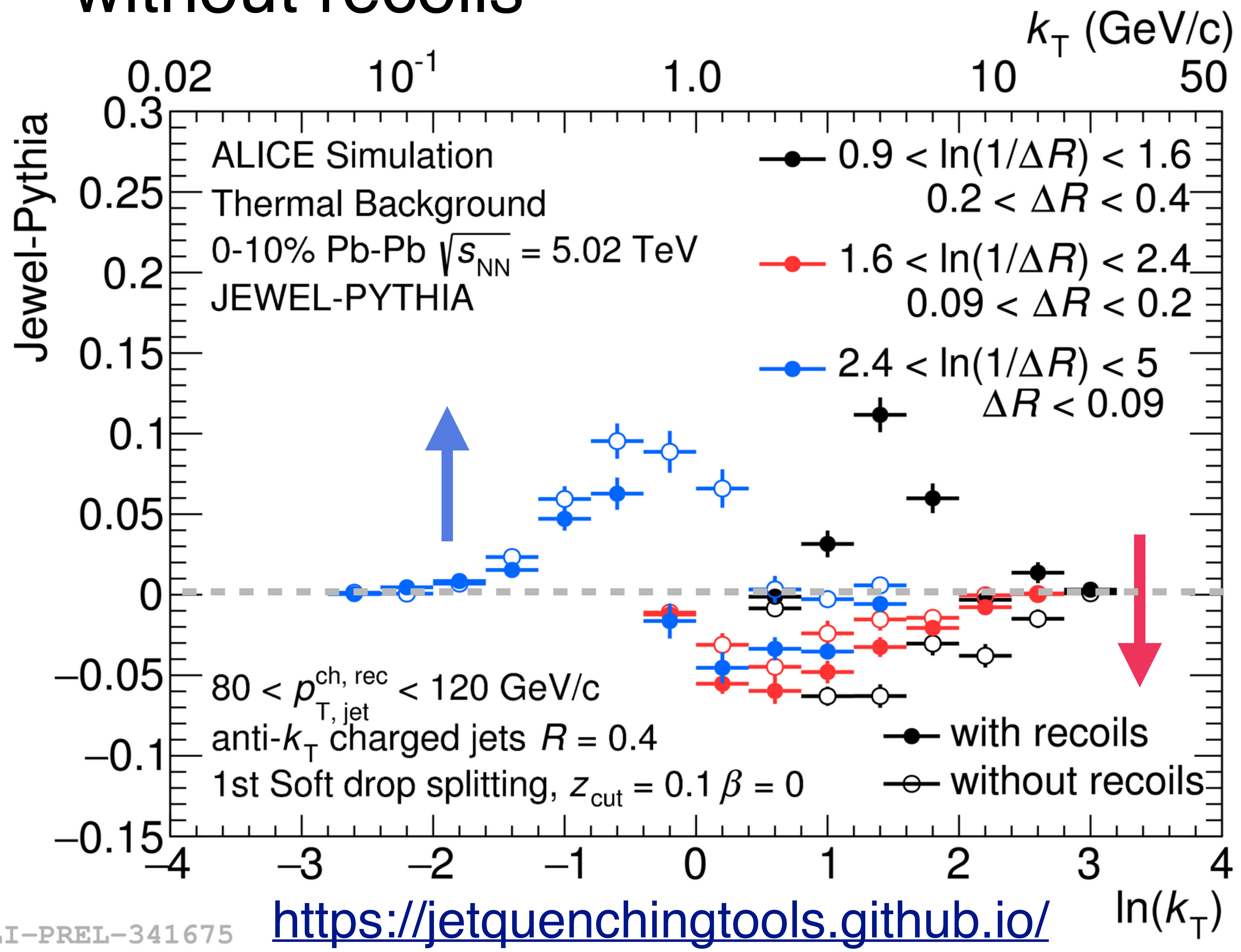
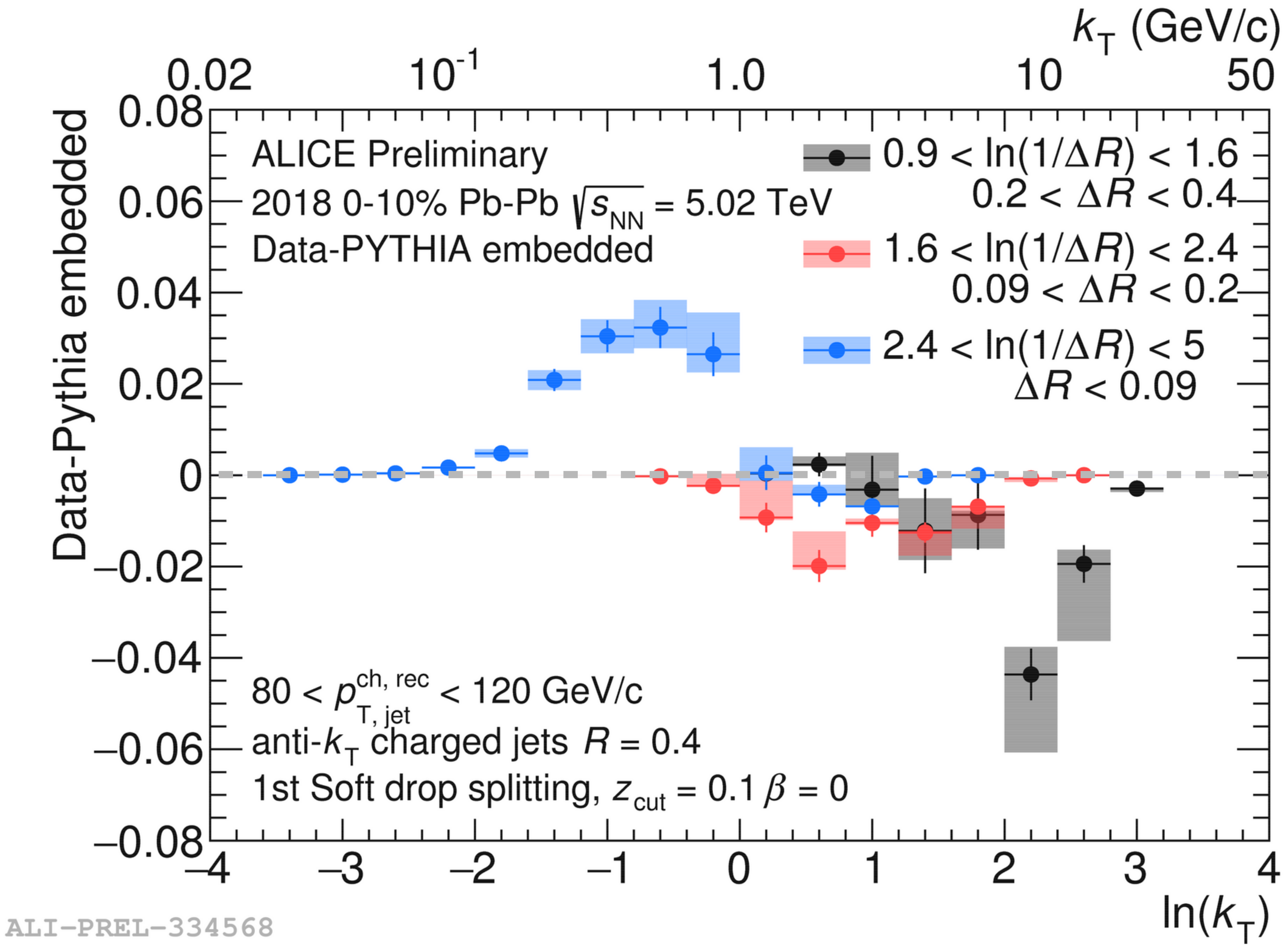
- JEWEL shows enhancement at small R

Lund Plane Projections

- Compare to JEWEL-PYTHIA embedded in a thermal background with and without recoils

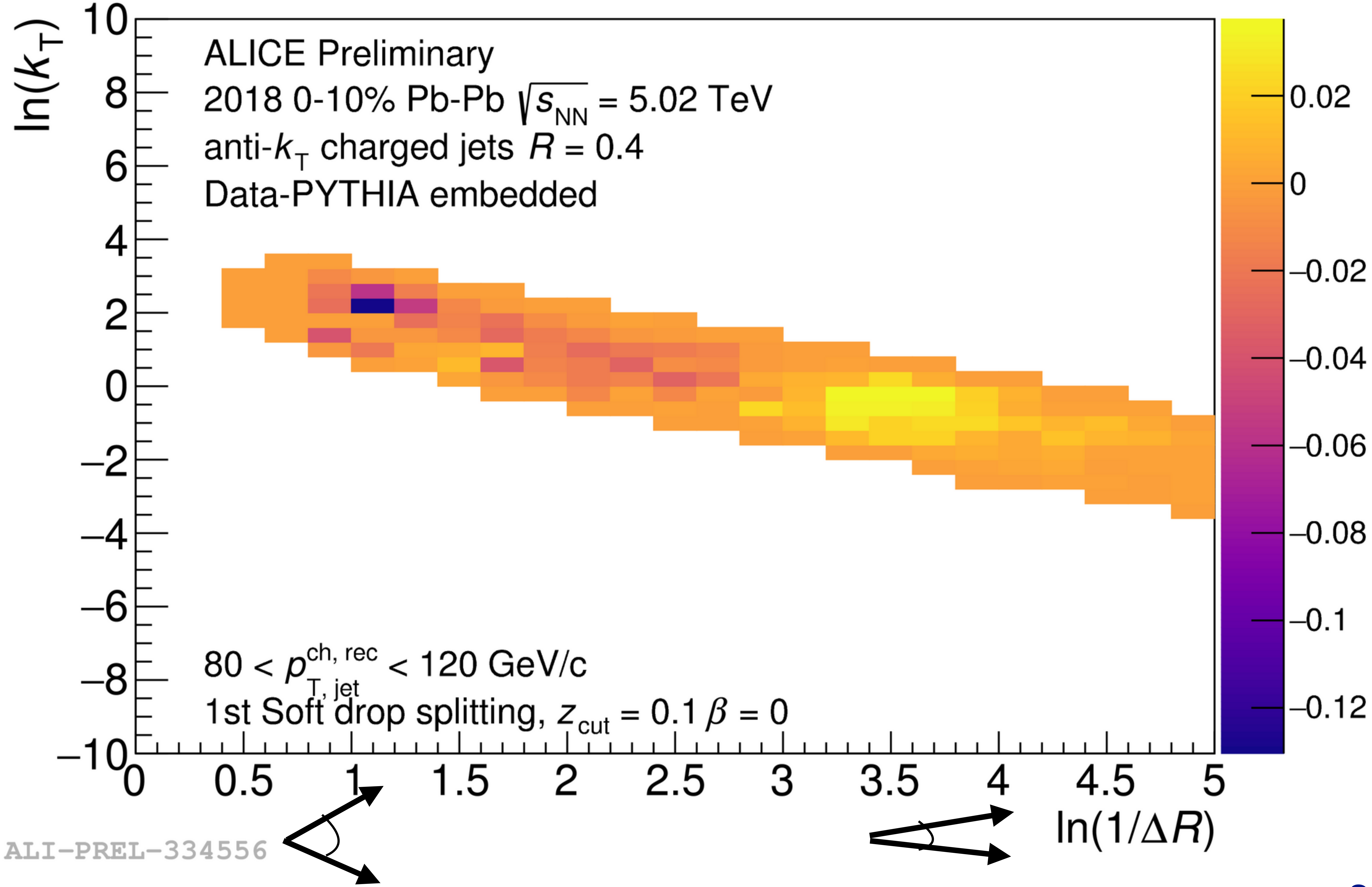




https://jetquenchingtools.github.io/

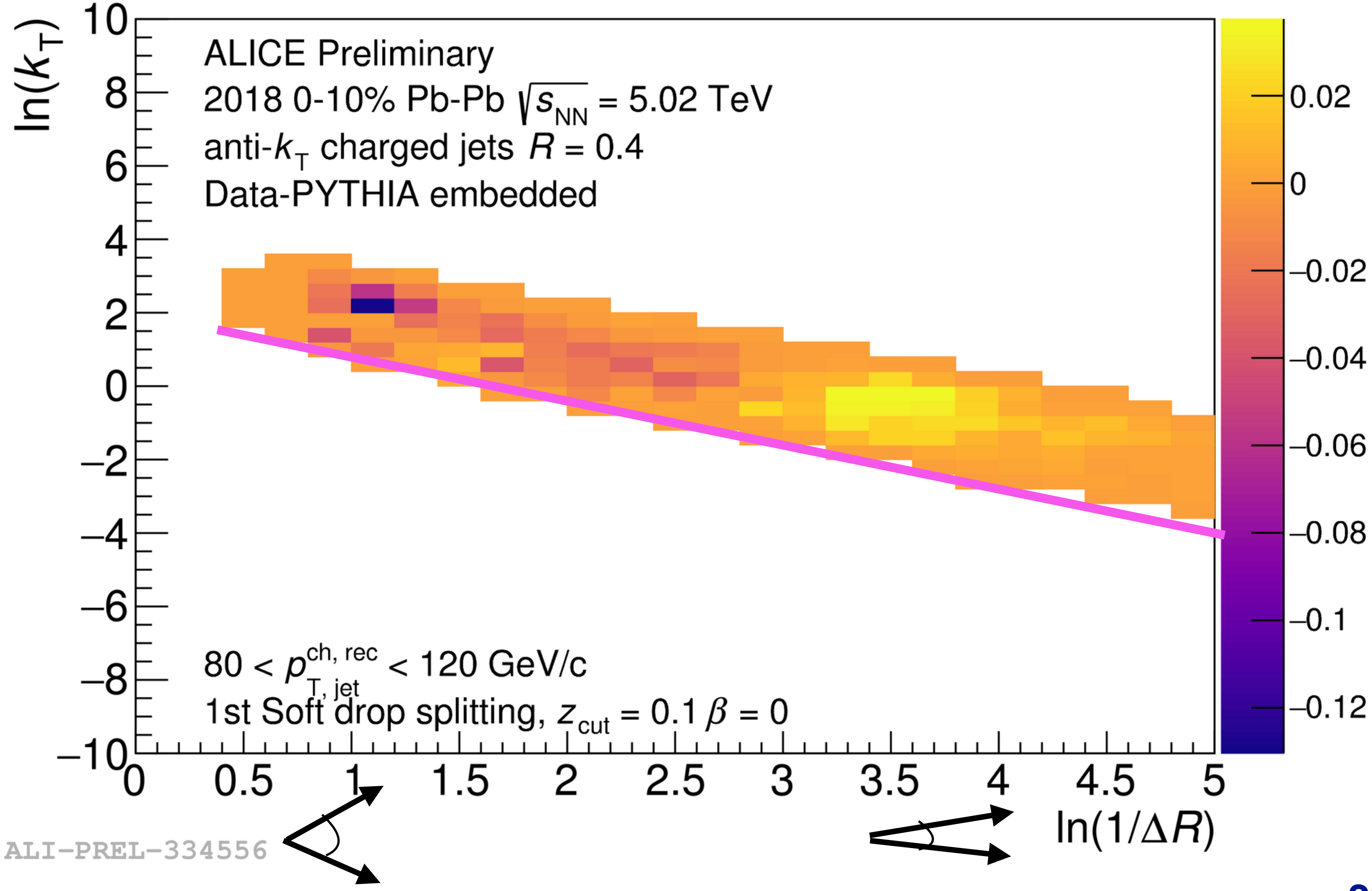
- JEWEL shows enhancement at small R
- JEWEL shows suppression at large R without recoils

Exploring the Lund Plane in Data



Exploring the Lund Plane in Data

- Soft drop (SD) grooming to access hard splitting



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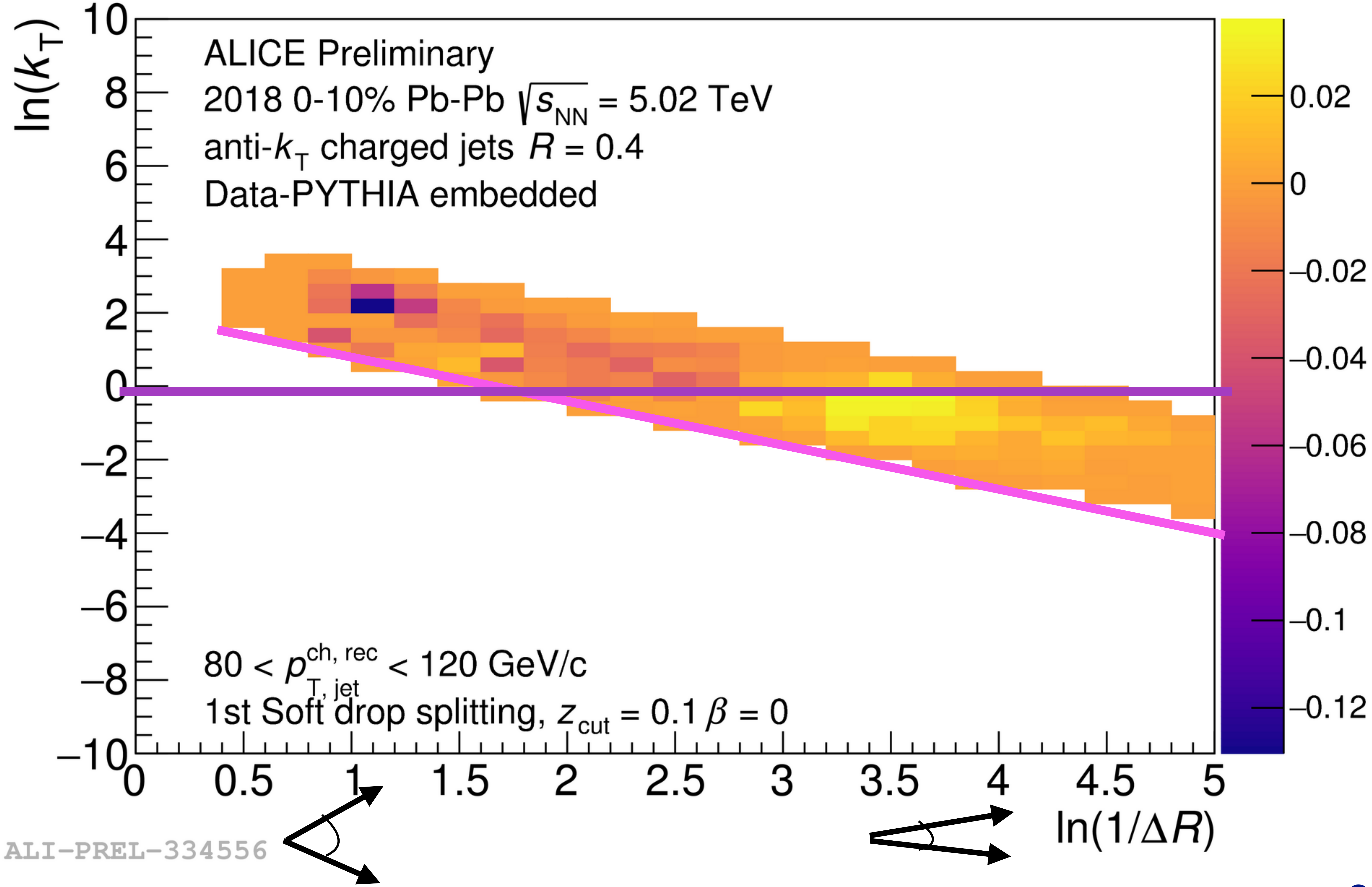
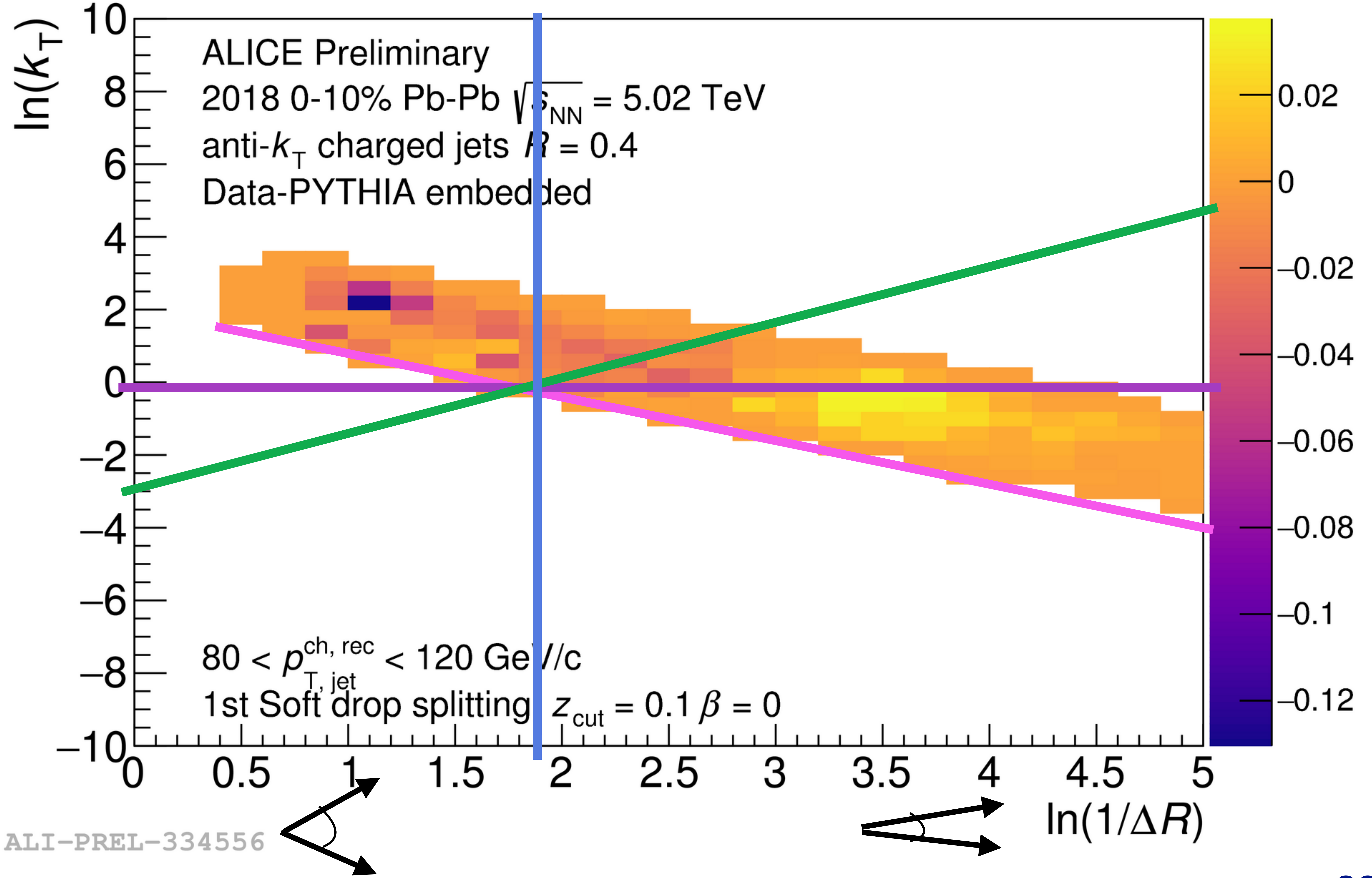
- Soft drop (SD) grooming to access hard splitting
- $\ln(k_T)>0$ cut to remove non-perturbative region



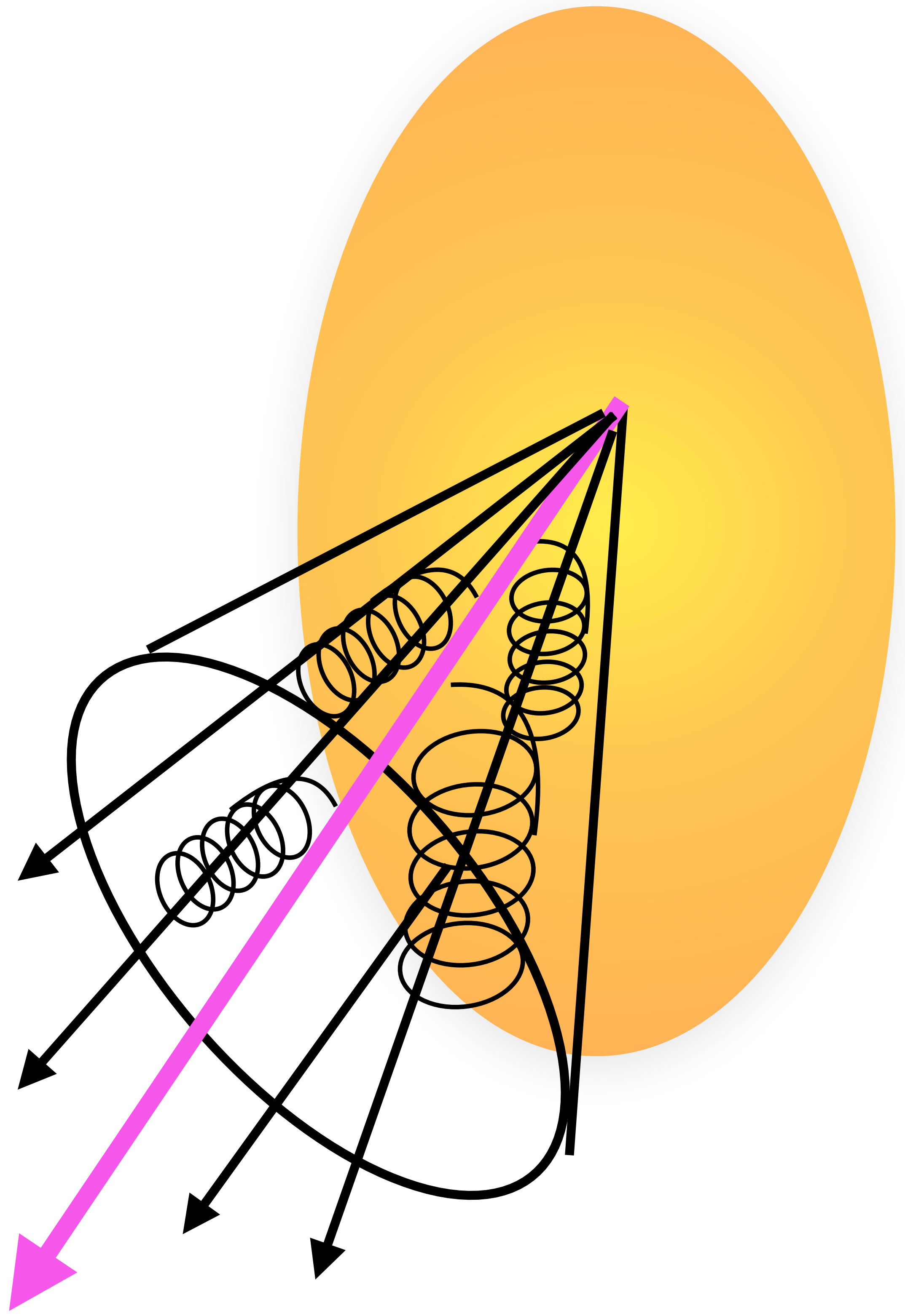
Exploring the Lund Plane in Data

- Soft drop (SD) grooming to access hard splitting
- $\ln(k_T)>0$ cut to remove non-perturbative region
- R_g explores time evolution of jet splitting



Groomed variables

- Soft drop grooming variables probe jet splitting



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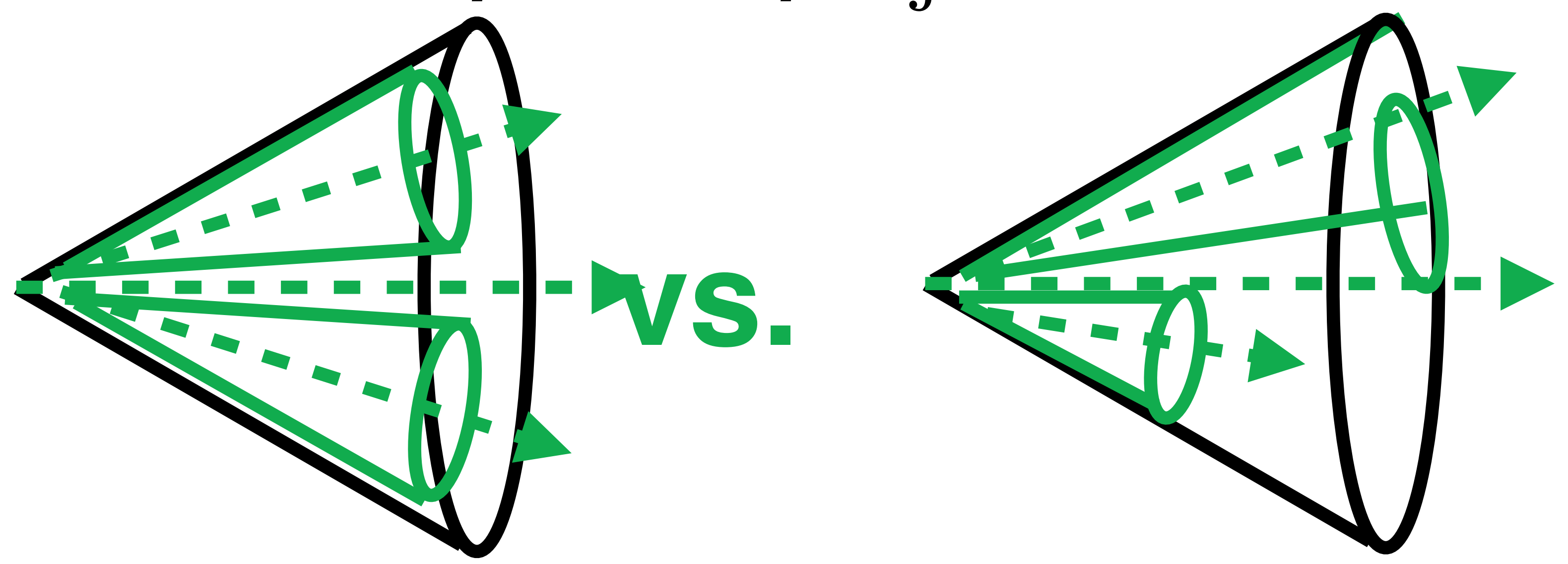
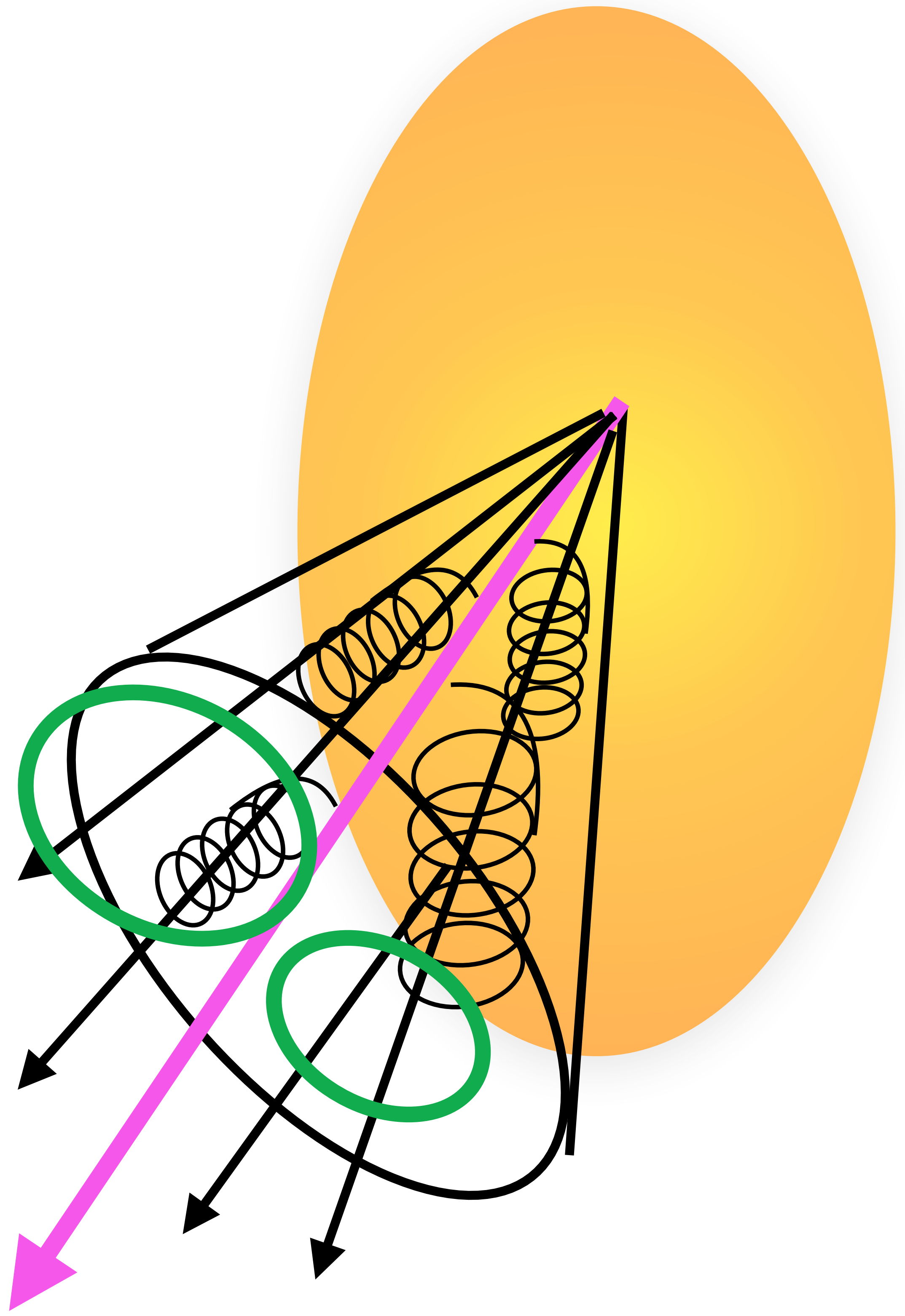
- Soft drop grooming variables probe jet splitting

➡ z_g: shared momentum fraction between two hardest subjets in parton shower

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

How symmetric is the jet splitting?





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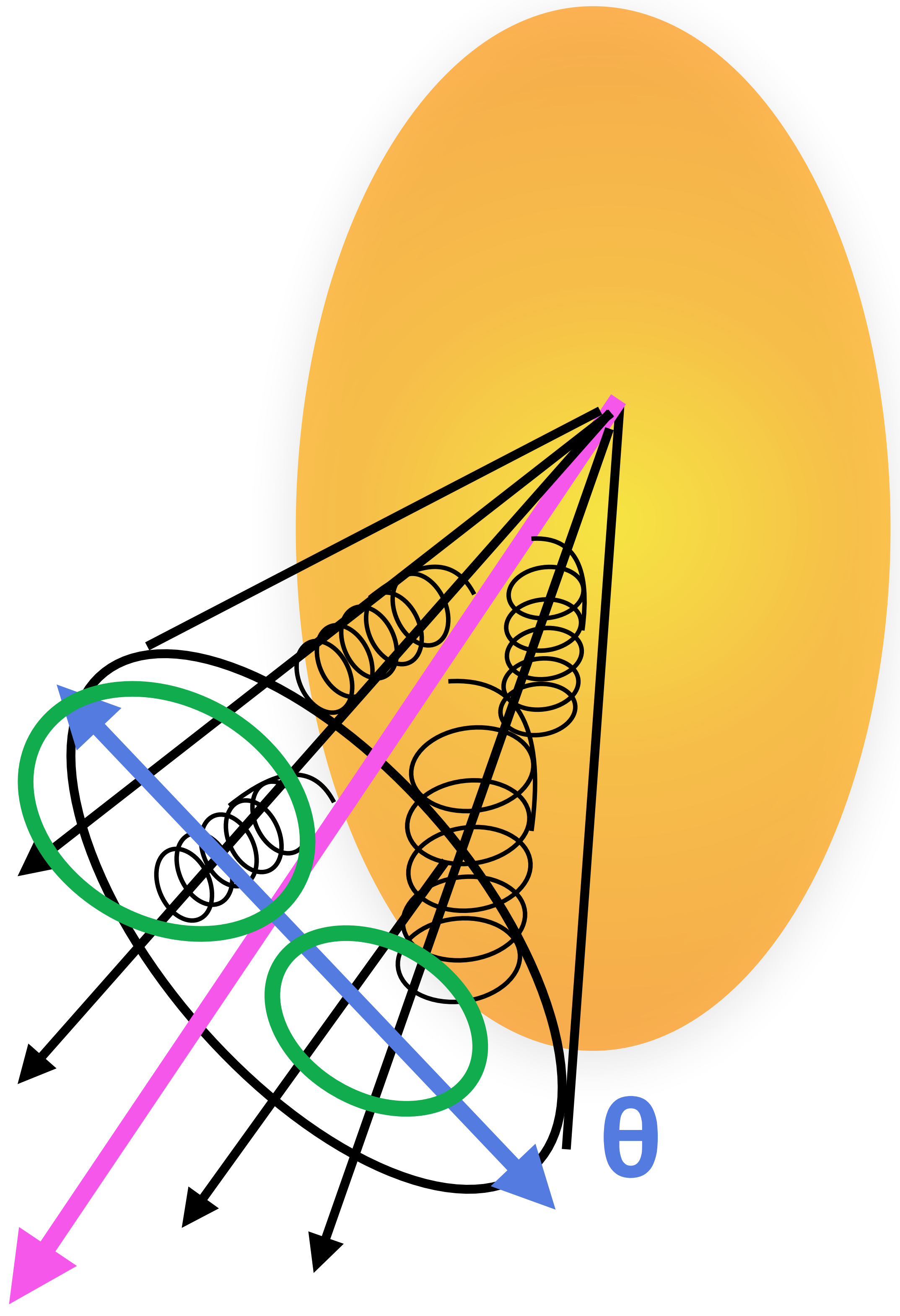

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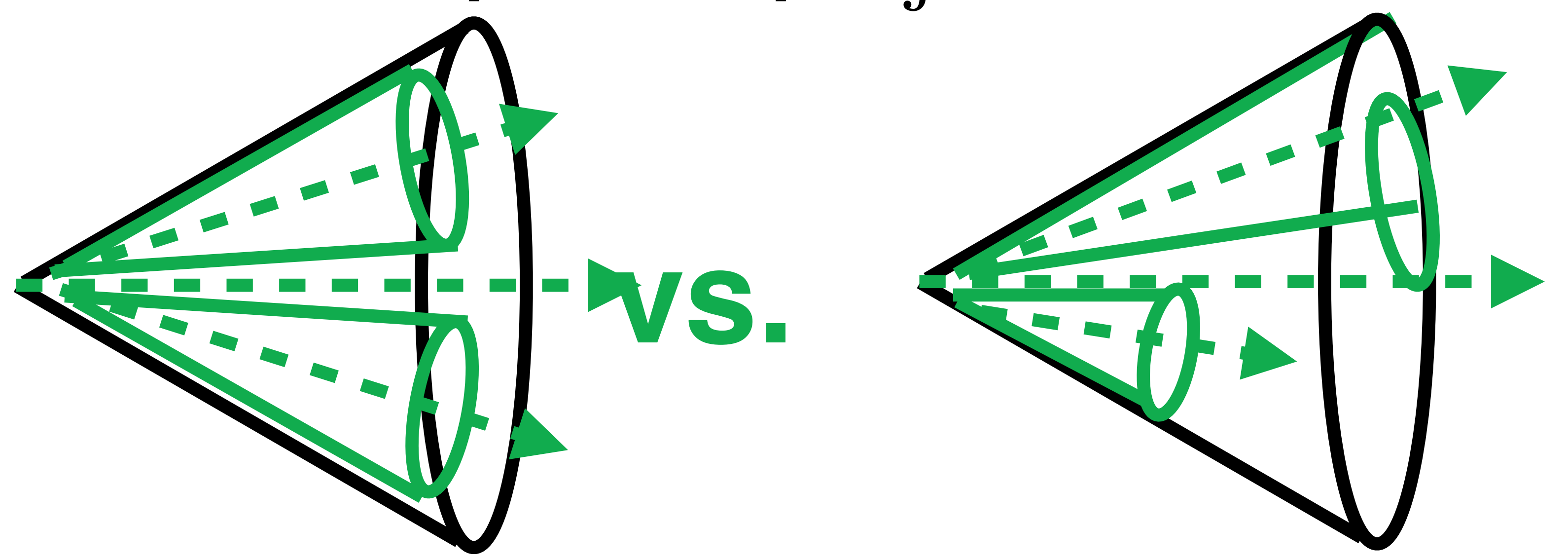
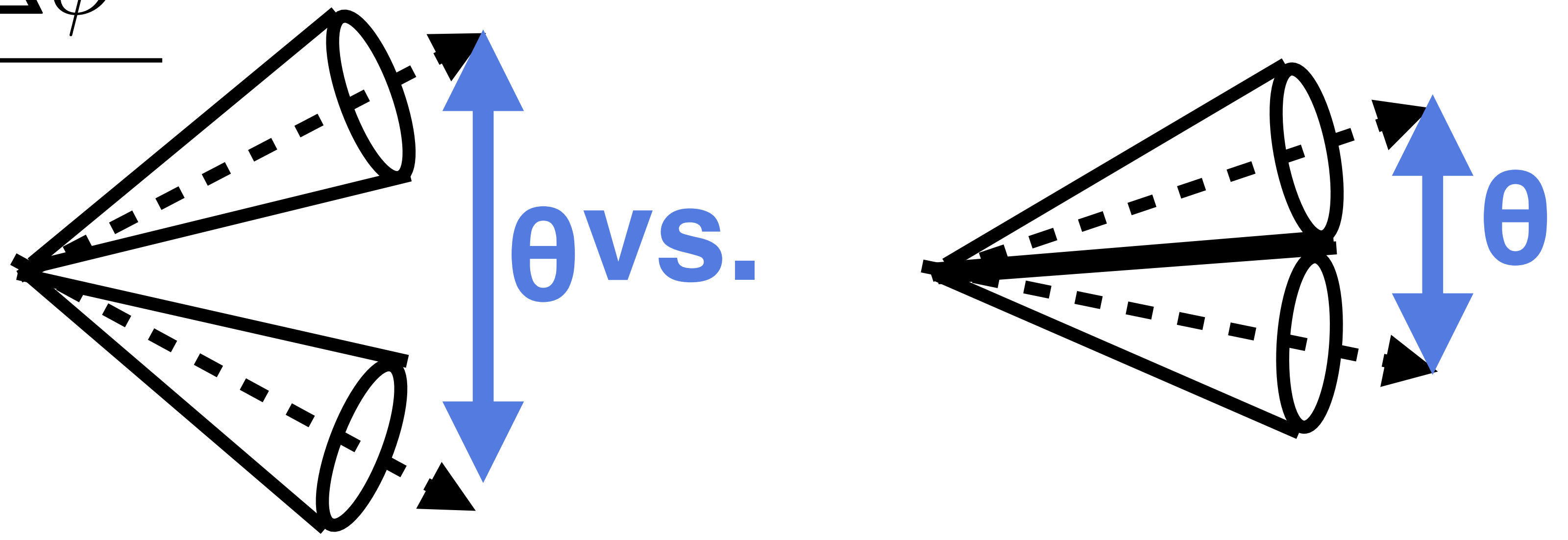


➡ θ_g: distance between subjets

$$\theta_g = \frac{R_g}{R} = \frac{\sqrt{\Delta\eta^2 + \Delta\phi^2}}{R}$$

How far apart are the subjets?



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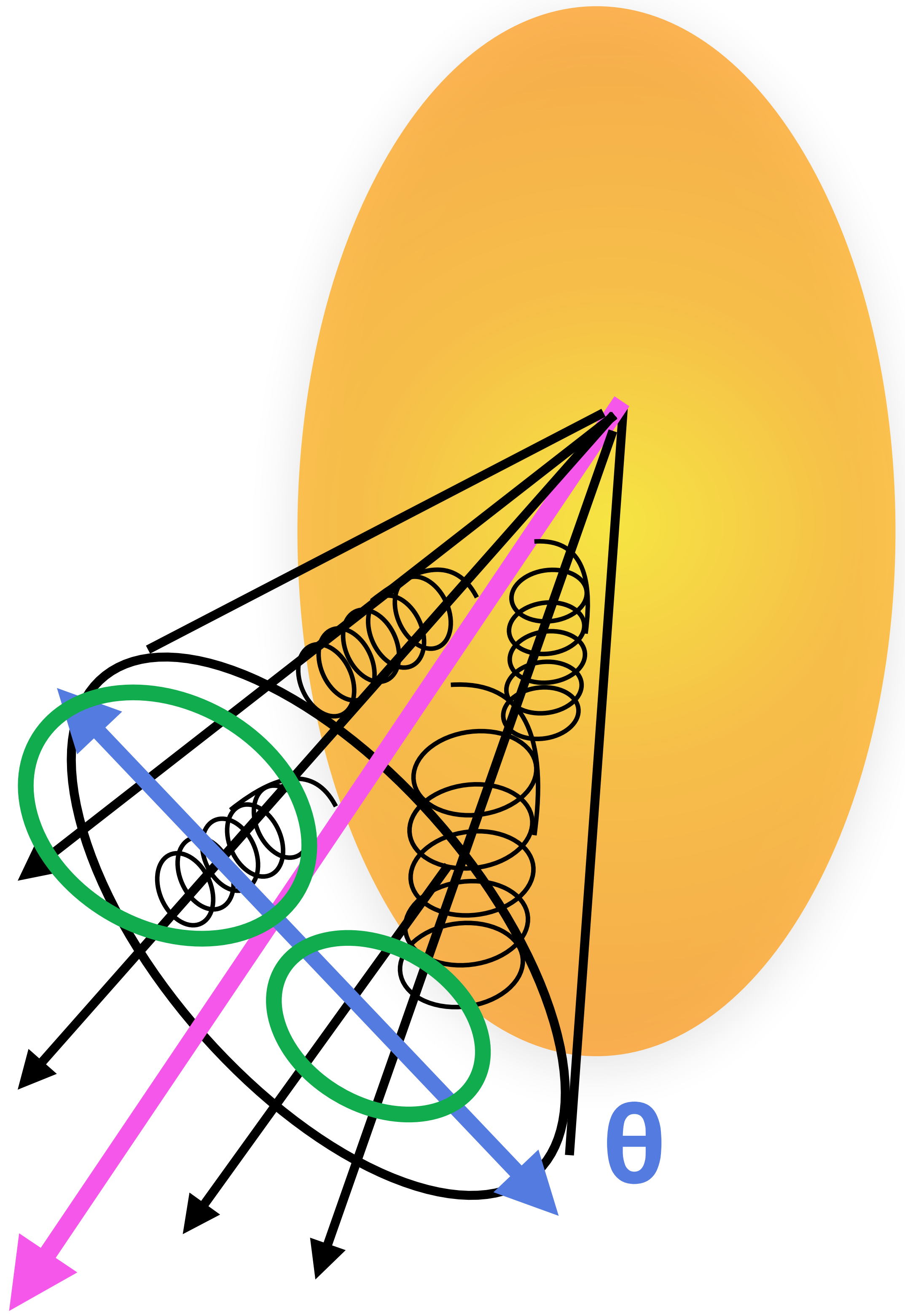

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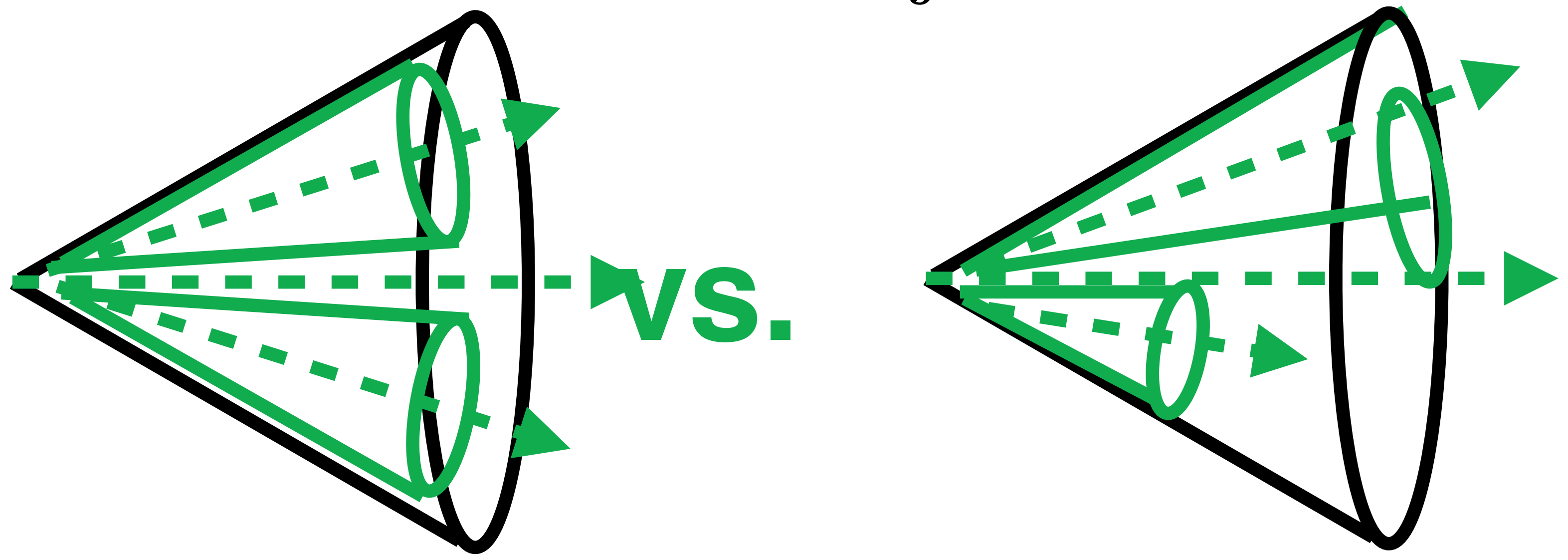

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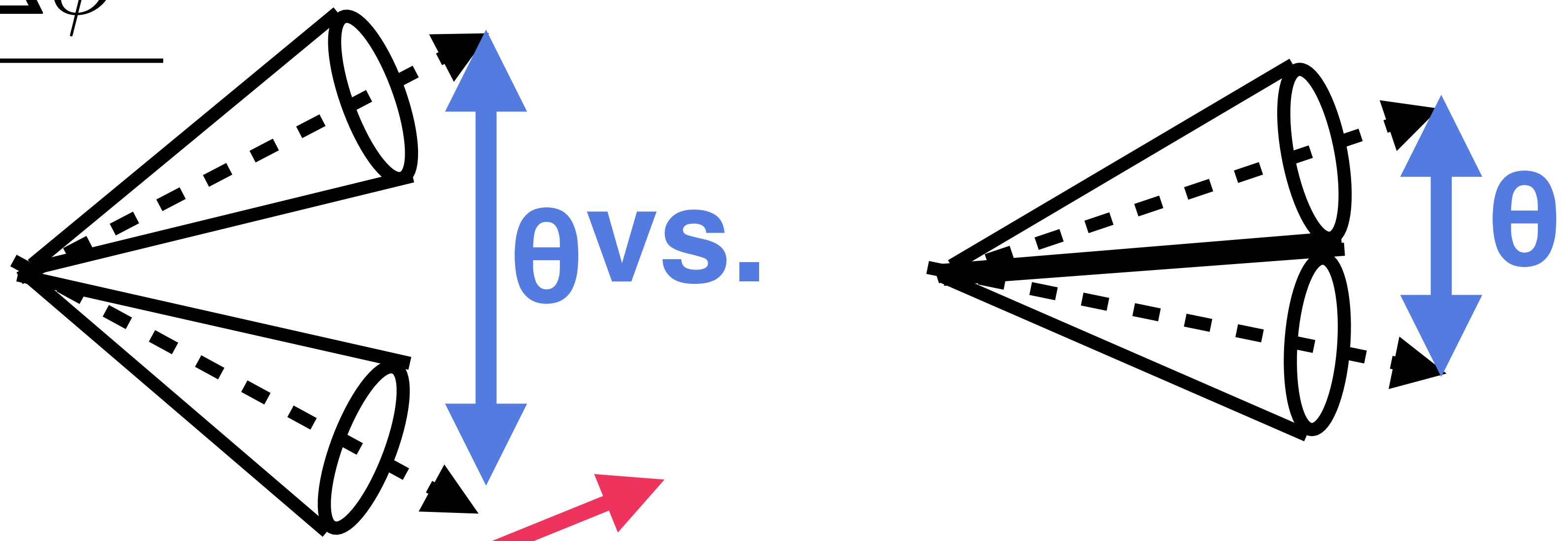
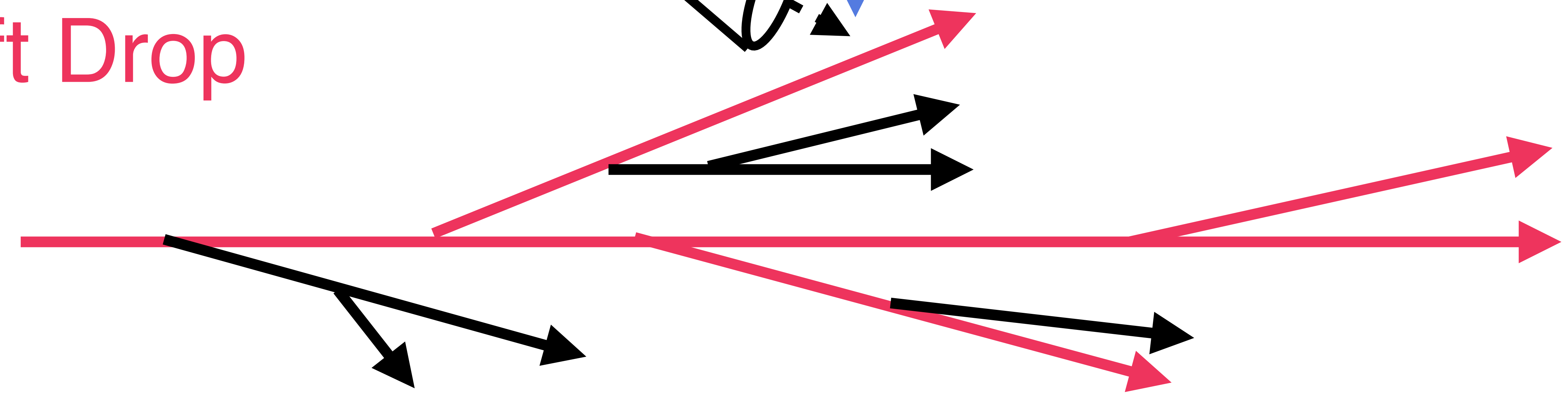


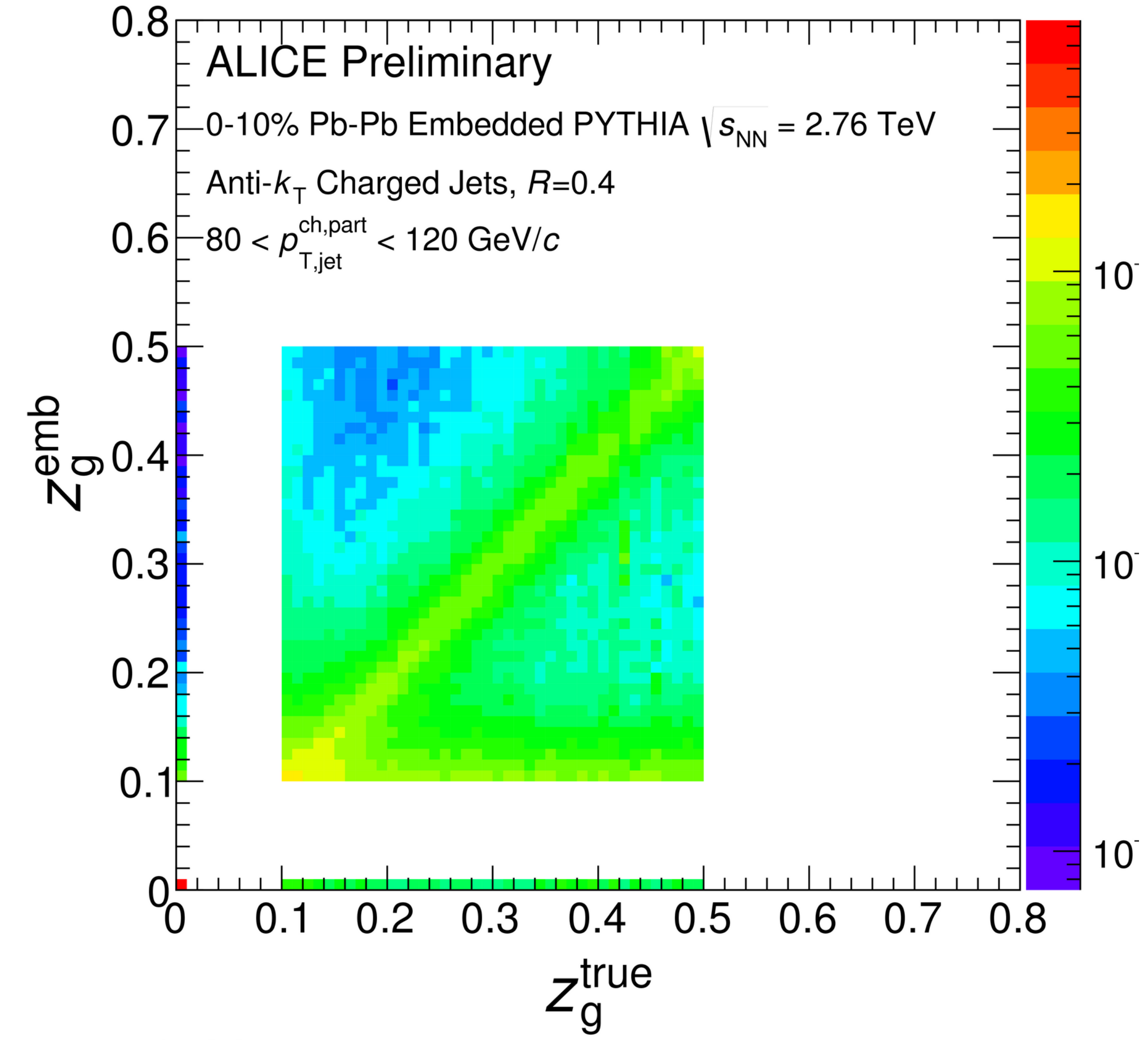
➡ n_{SD}: number of splittings passing Soft Drop

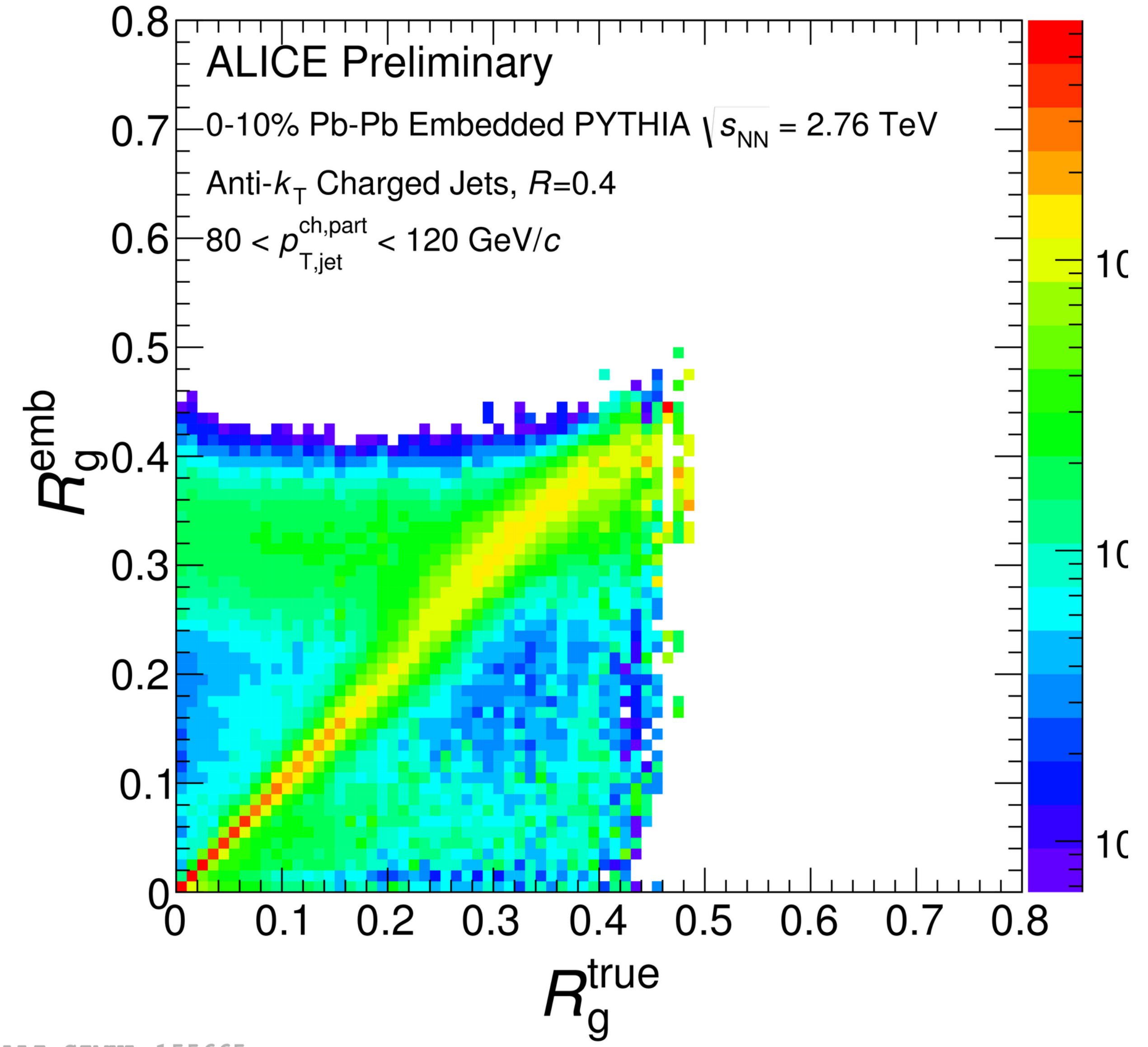
Number of subjets within a jet?

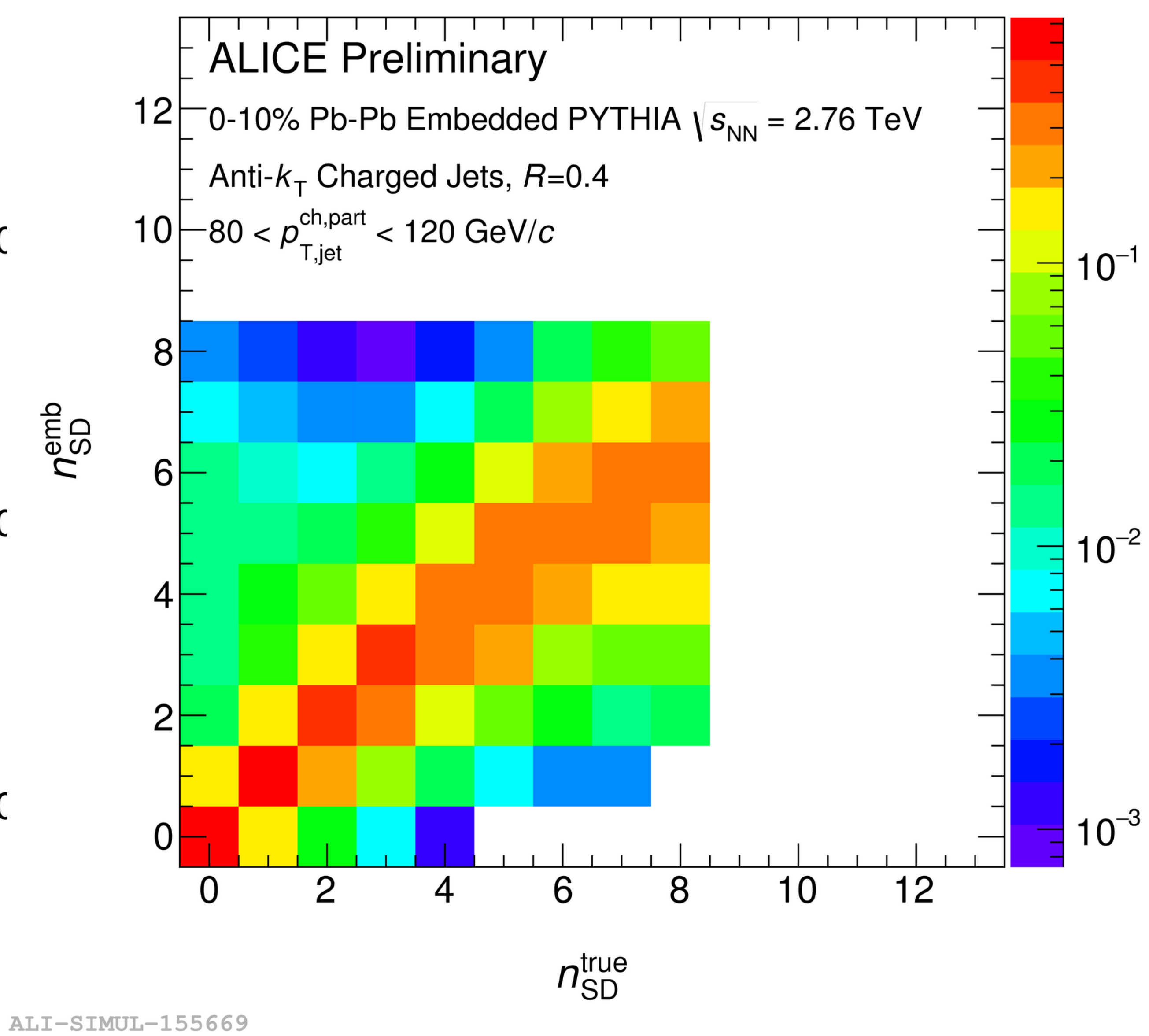


Background treatment

- Uncorrelated background leads to subjets being picked up as incorrect or "fake" splittings







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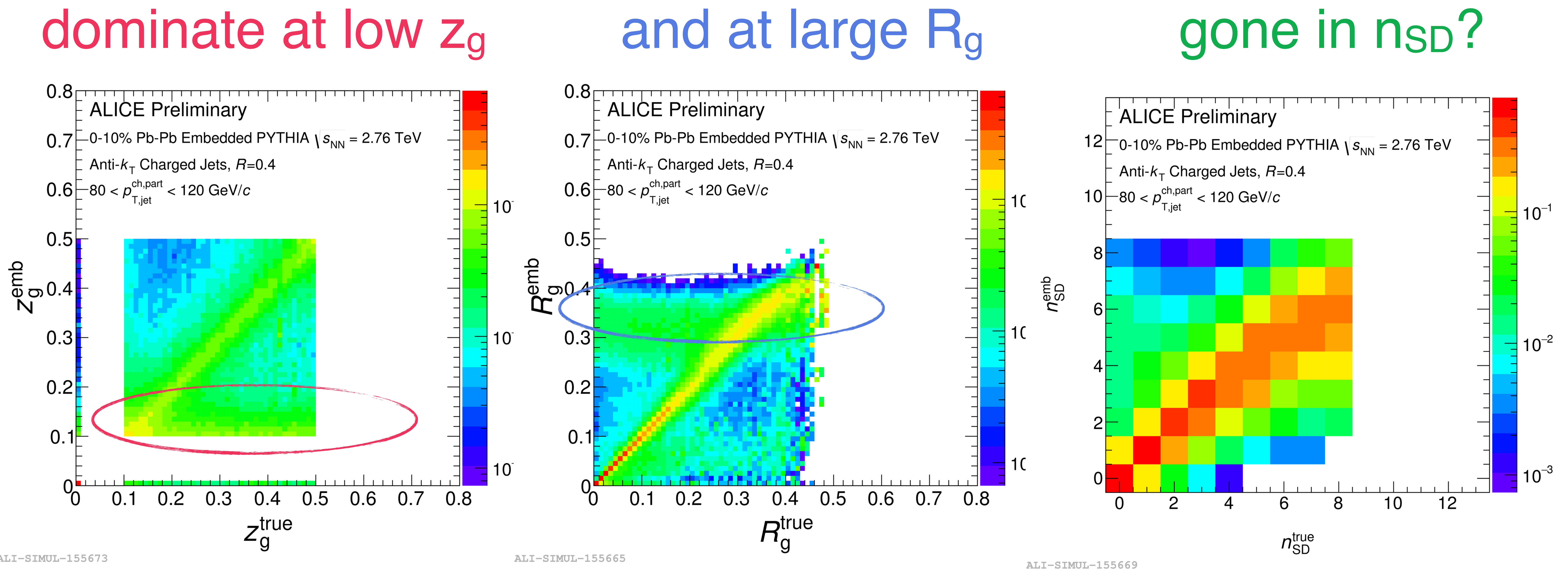

▸ *Non-diagonal response prohibits unfolding*

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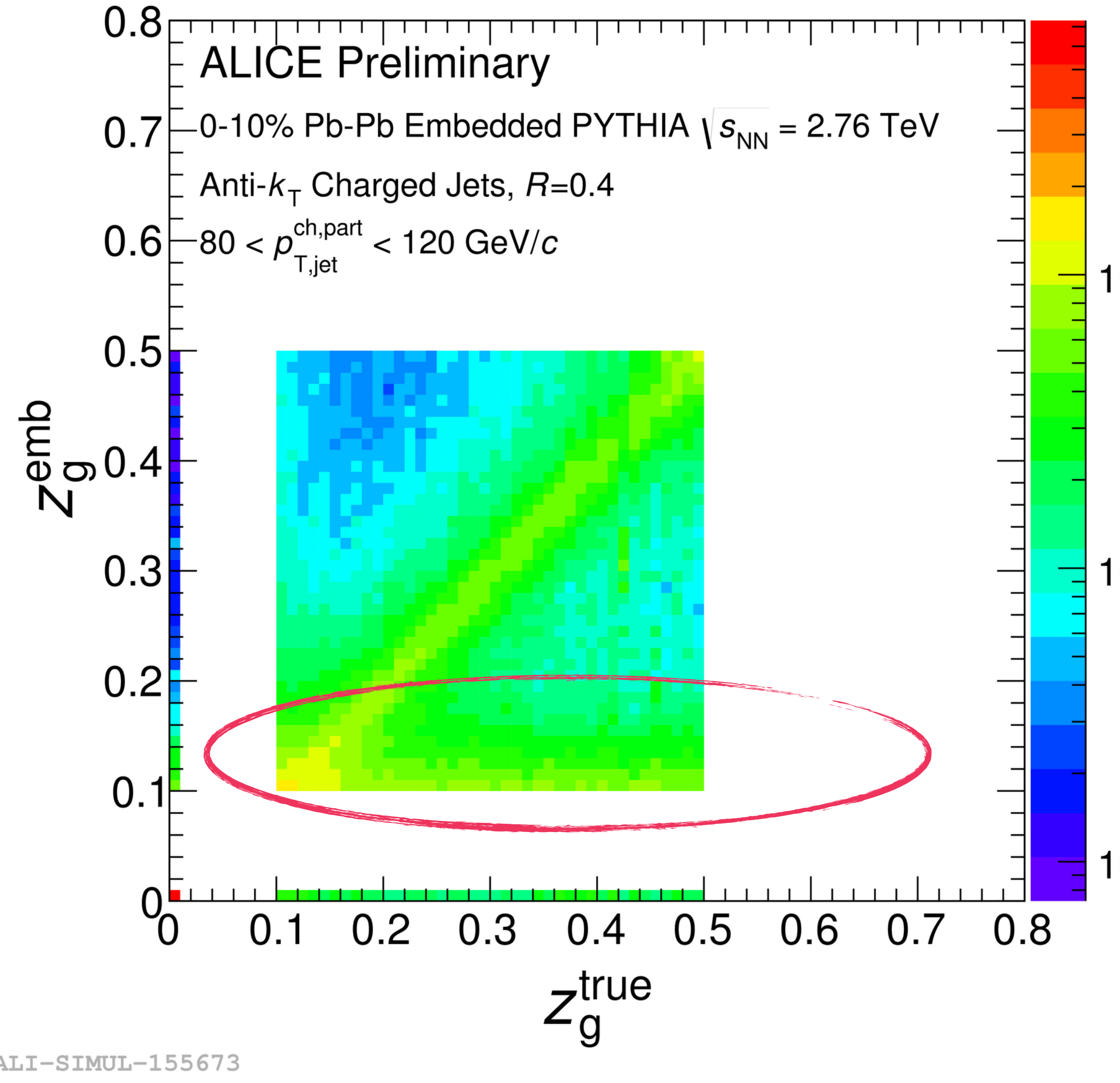
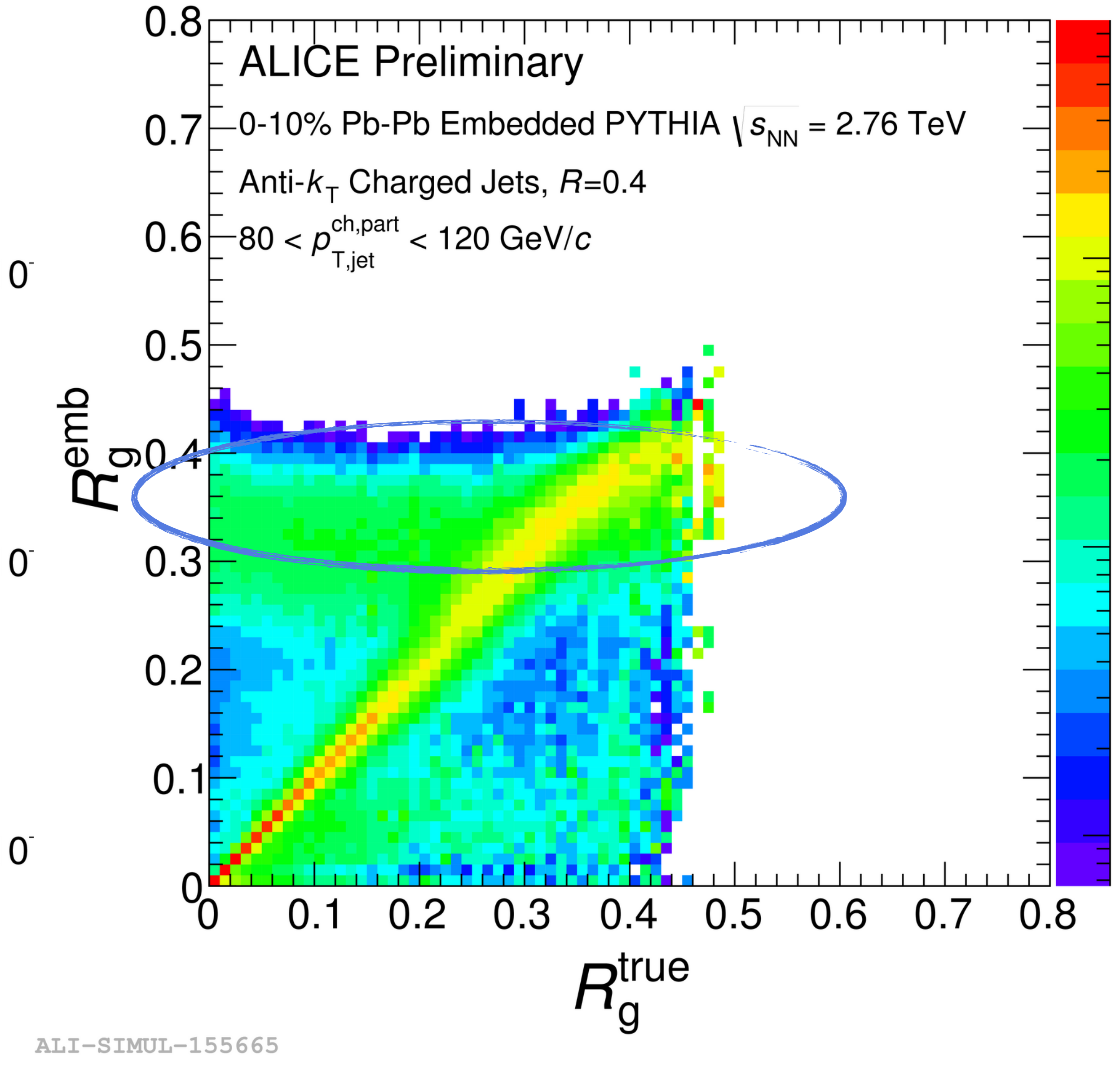
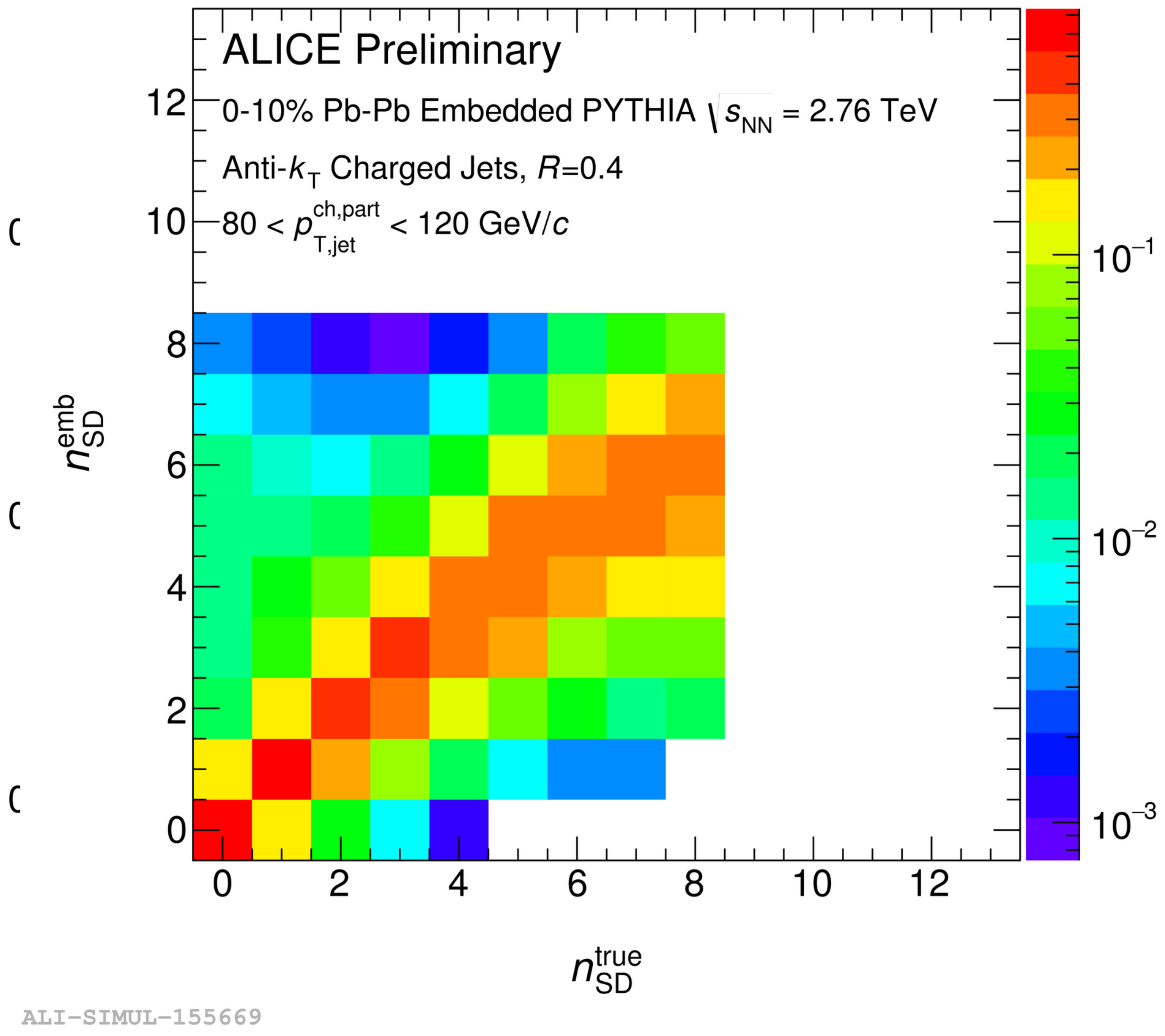
dominate at low z_g



and at large R_g



gone in n_{SD}?



▸ *Non-diagonal response prohibits unfolding*

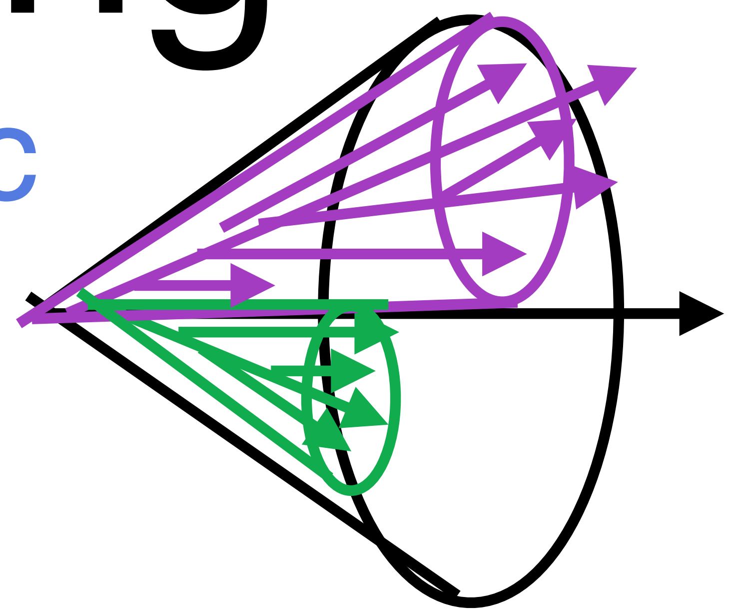
- Embed PYTHIA8 into Pb-Pb data as a reference to mimic background effects

➡*Caveat*: in combinatoric dominated regions, differences seen in observables can't be attributed only to quenching *if* the background splittings differ largely for medium vs. vacuum jet fragmentation

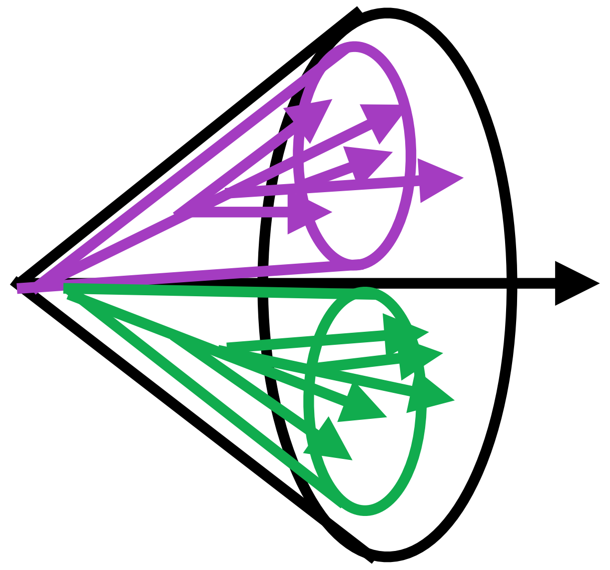
z_g: jet splitting

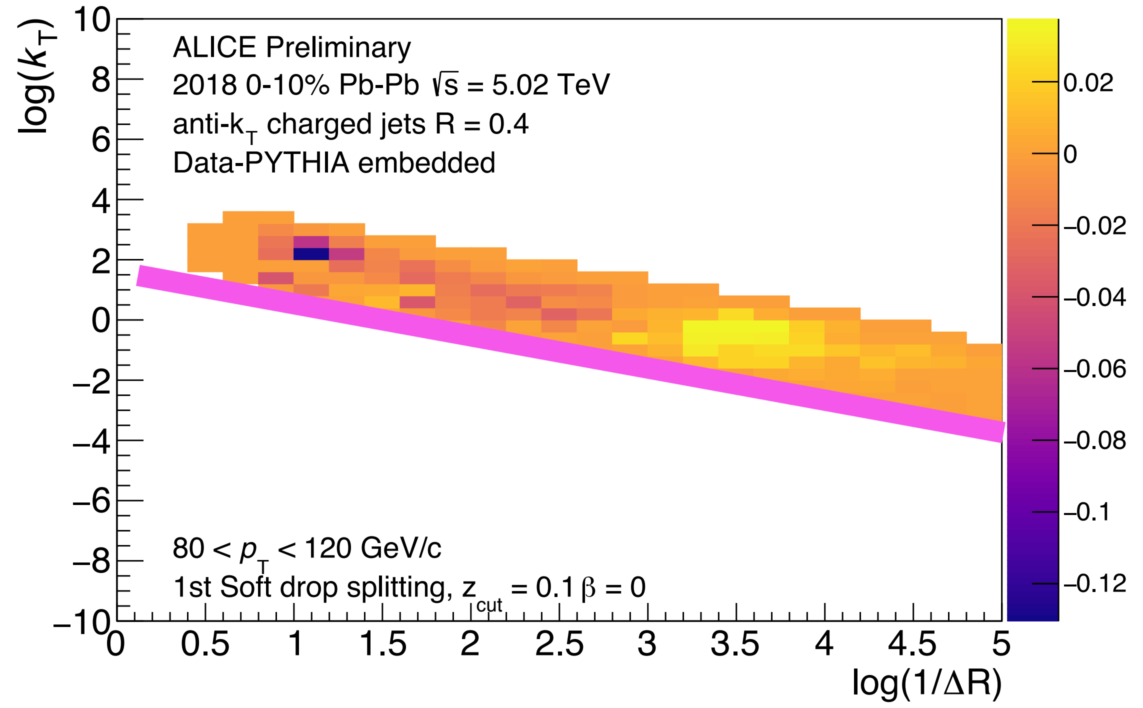
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

asymmetric splitting: low z_g



symmetric splitting: high z_g

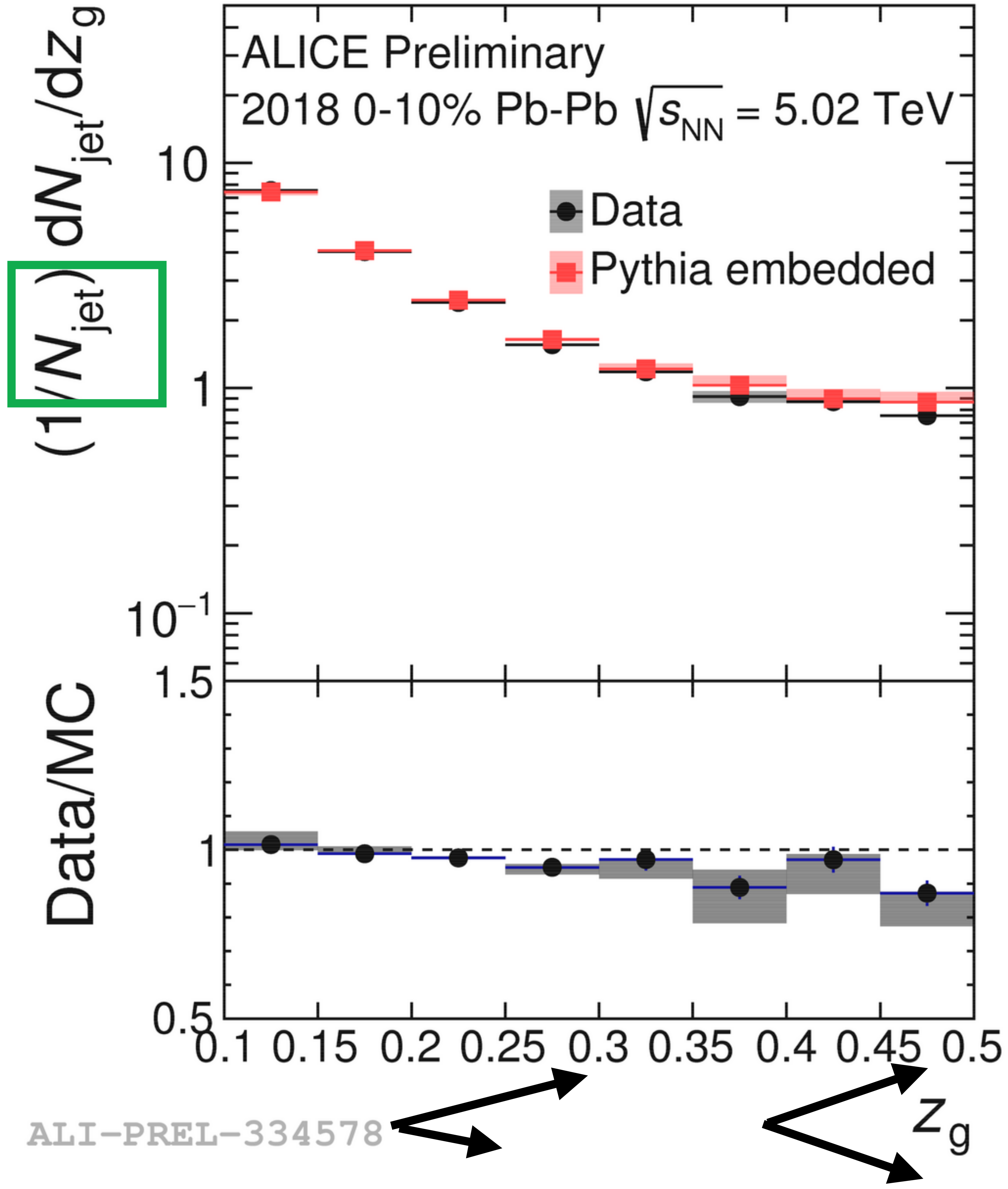




- 5.02 TeV 0-10% Pb-Pb collisions compared to embedded MC

- Dominant systematics
  - Data: tracking inefficiency
  - MC: reweighing Pythia to Herwig for model dependence

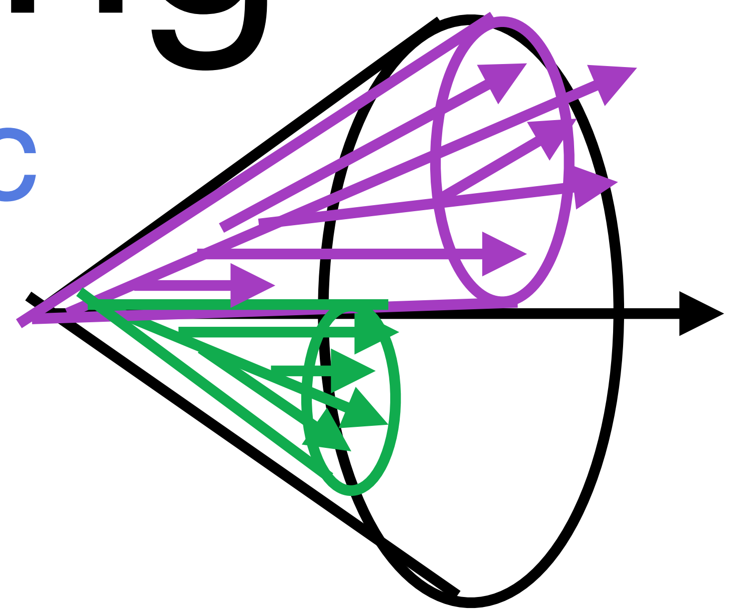
Njets: all jets in p_T bin



z_g: jet splitting

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

asymmetric splitting: low z_g



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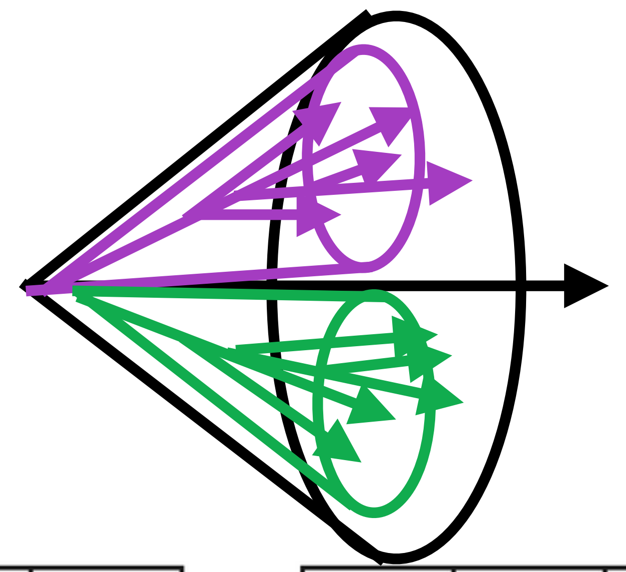
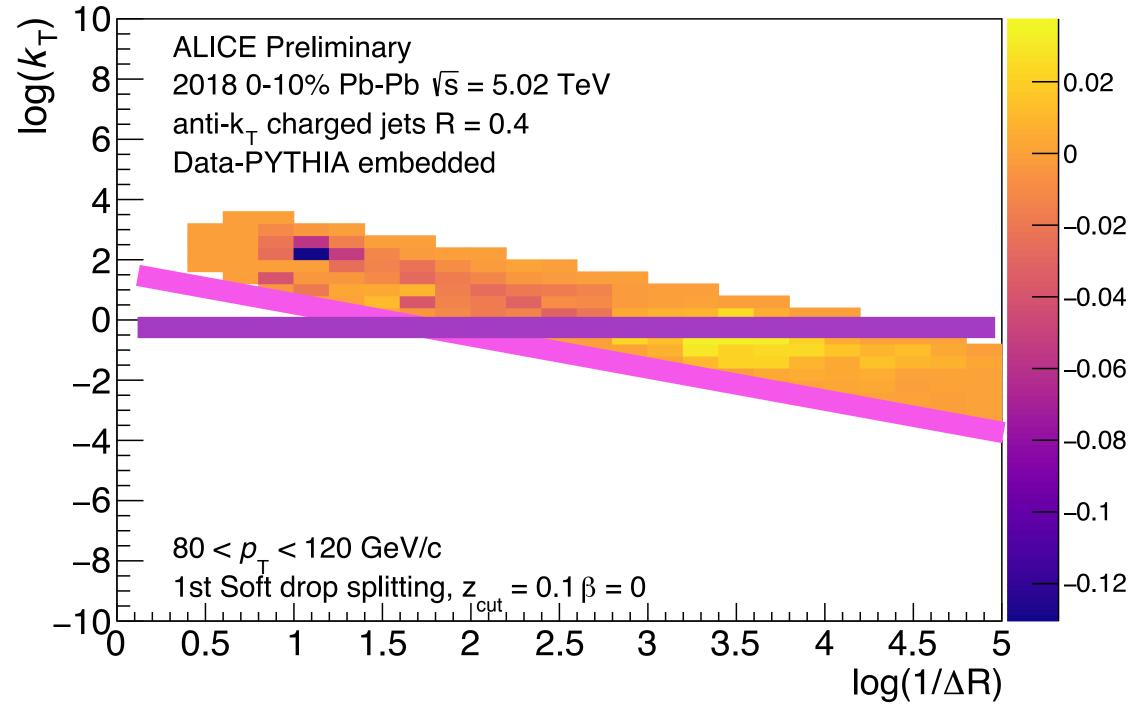
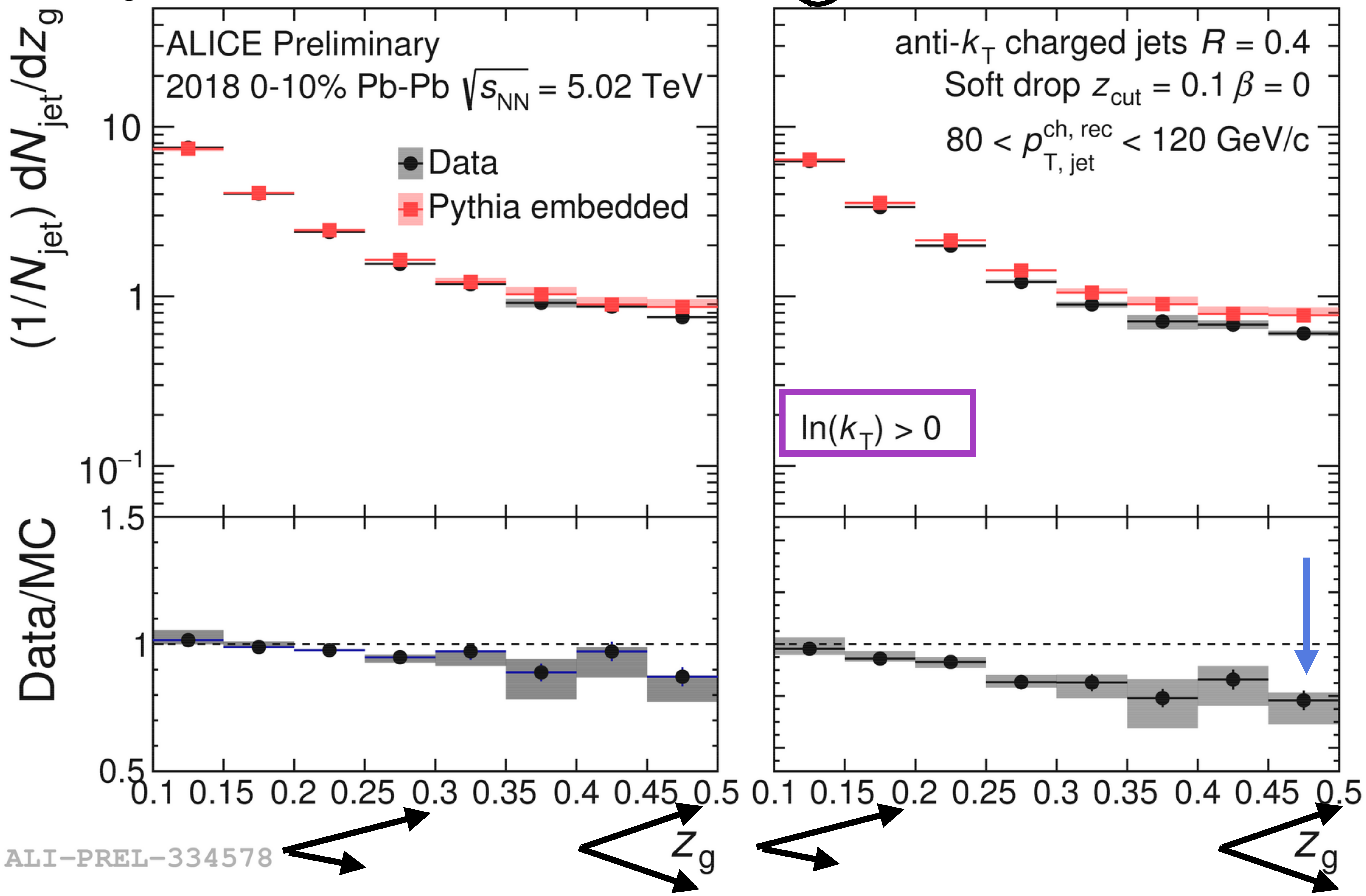
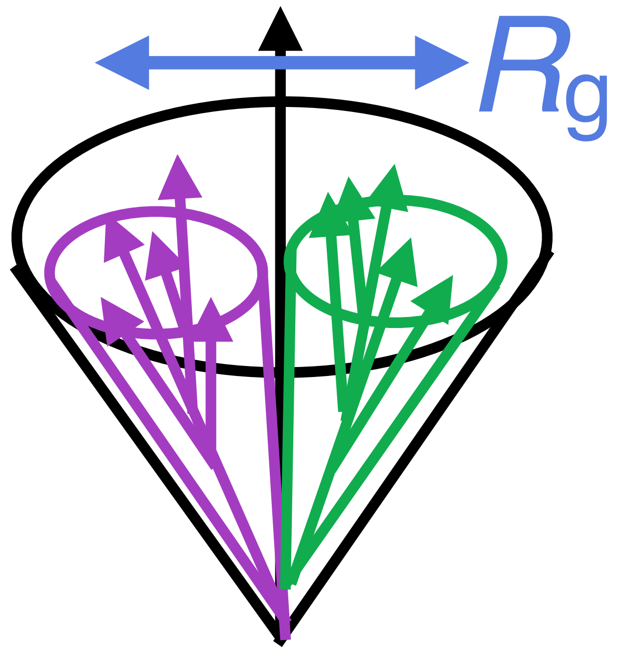


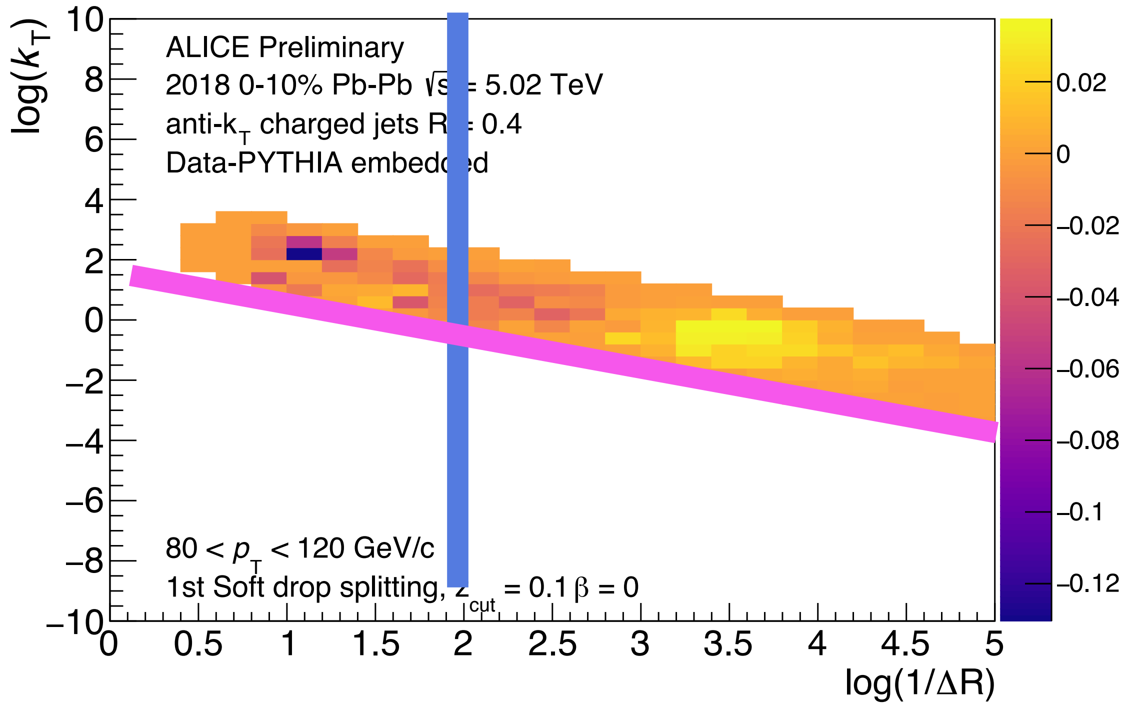


- 5.02 TeV 0-10% Pb-Pb collisions compared to embedded MC
- ln(kT) cut steepens the spectrum in data
- Suppression of symmetric splittings

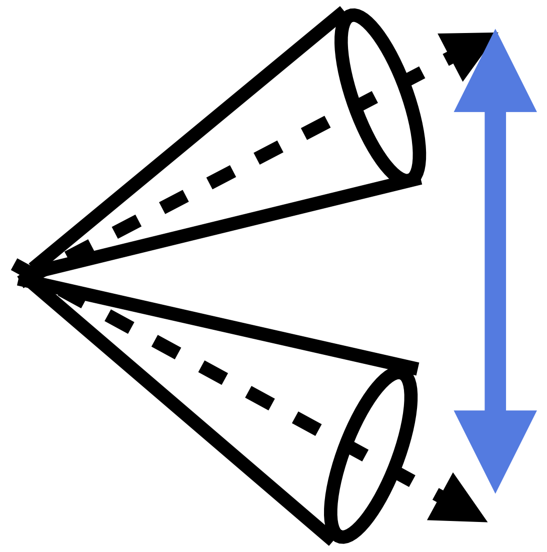


z_g: opening angle

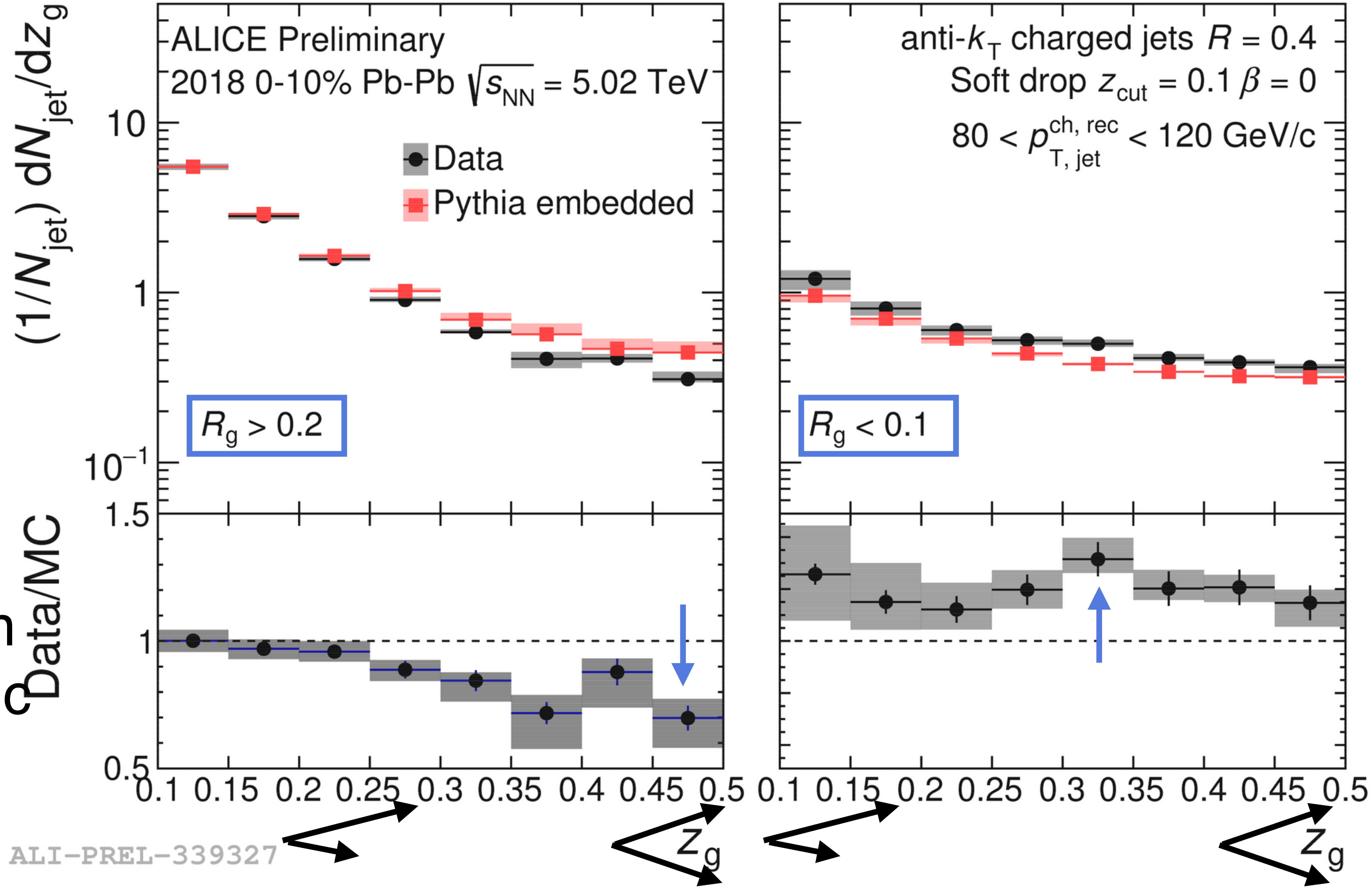




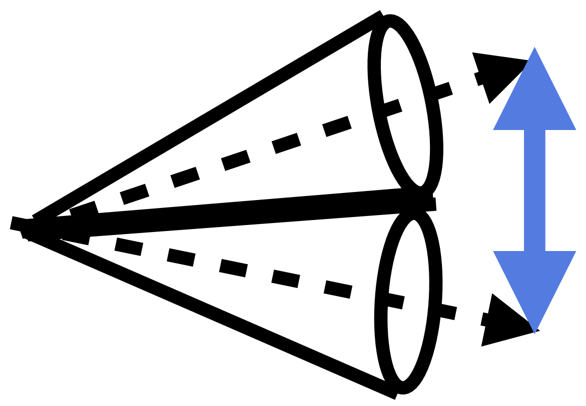
wide
$R_g > 0.2$



- Wide: more significant suppression of symmetric splittings

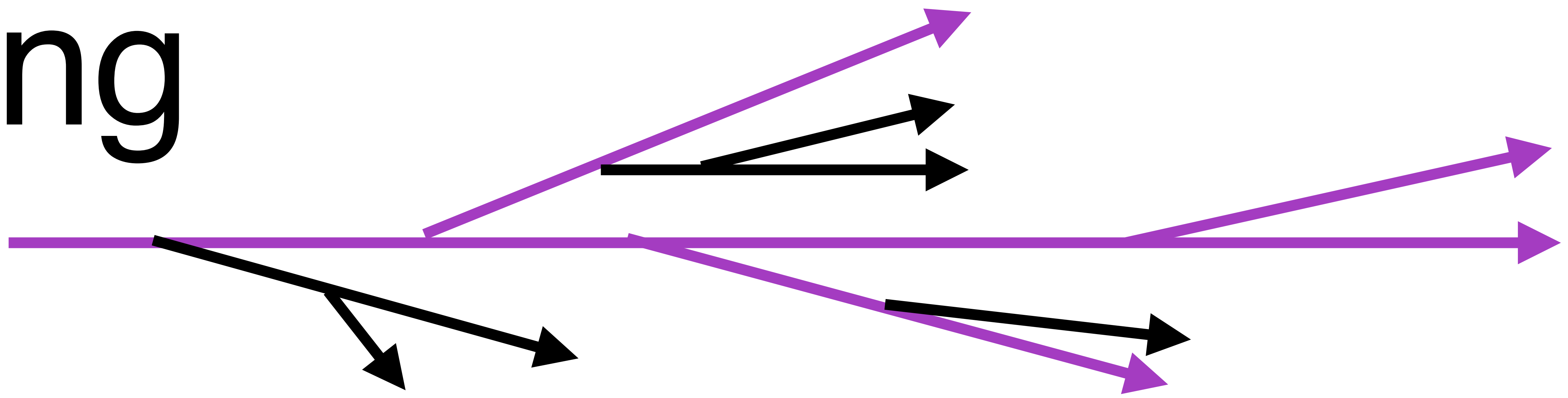


collimated
$R_g < 0.1$



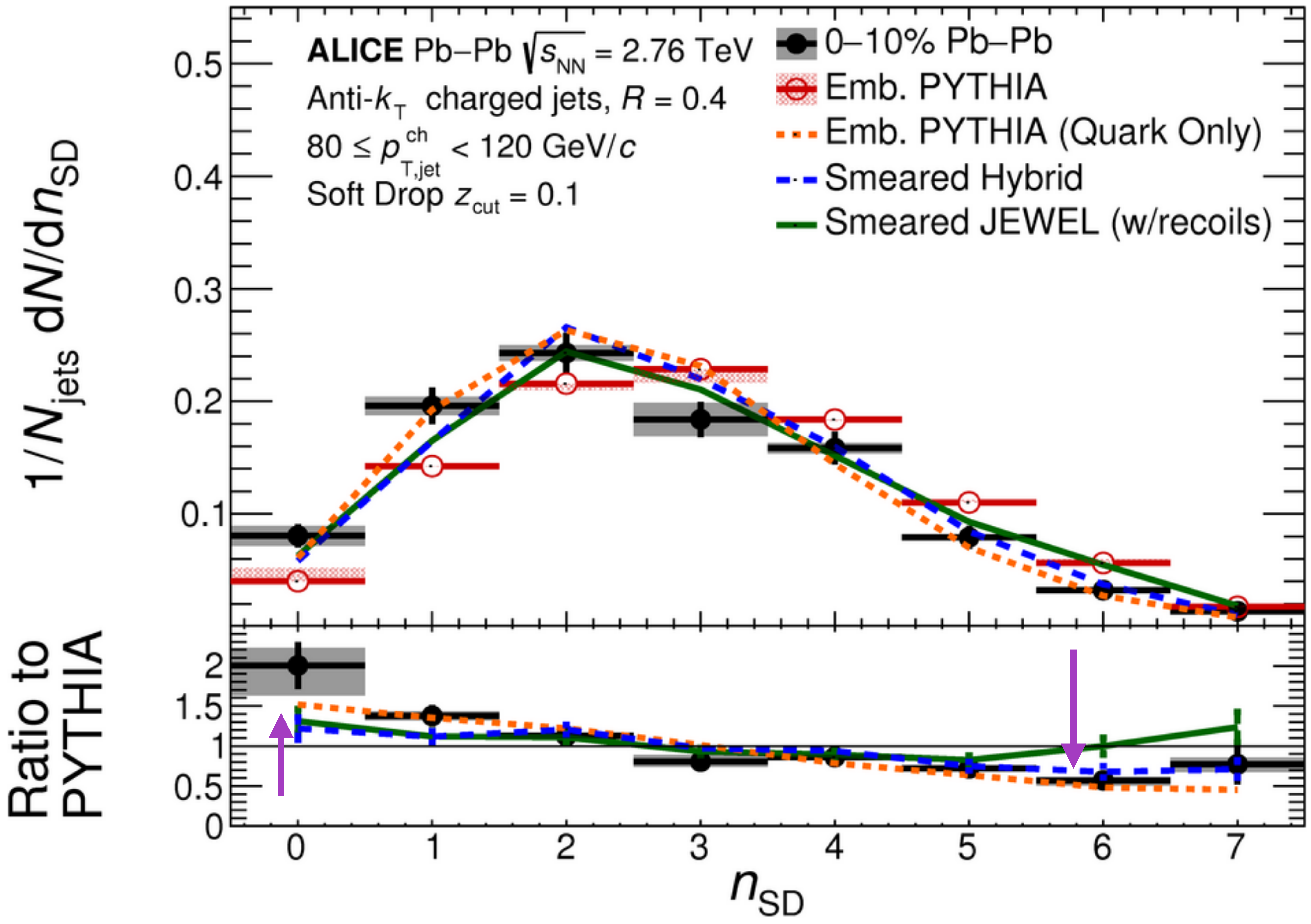
- Narrow splittings enhanced

n_{SD}: iterative declustering



- Previous ALICE publication of 0-10% Pb-Pb data at 2.76 TeV
  arXiv:1905.02512v1

- Hint of shift towards lower numbers of splittings



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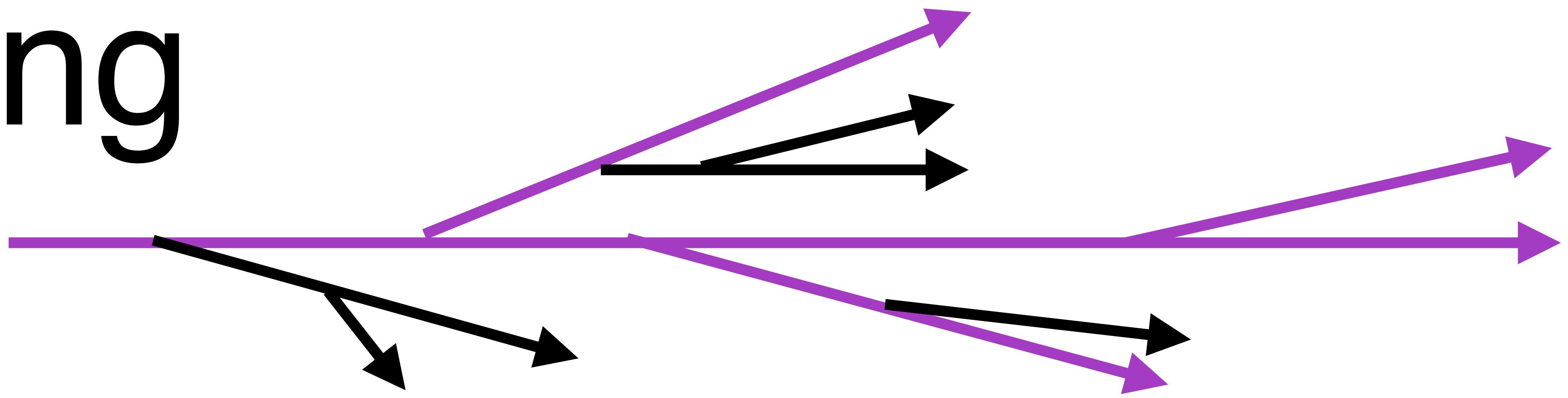
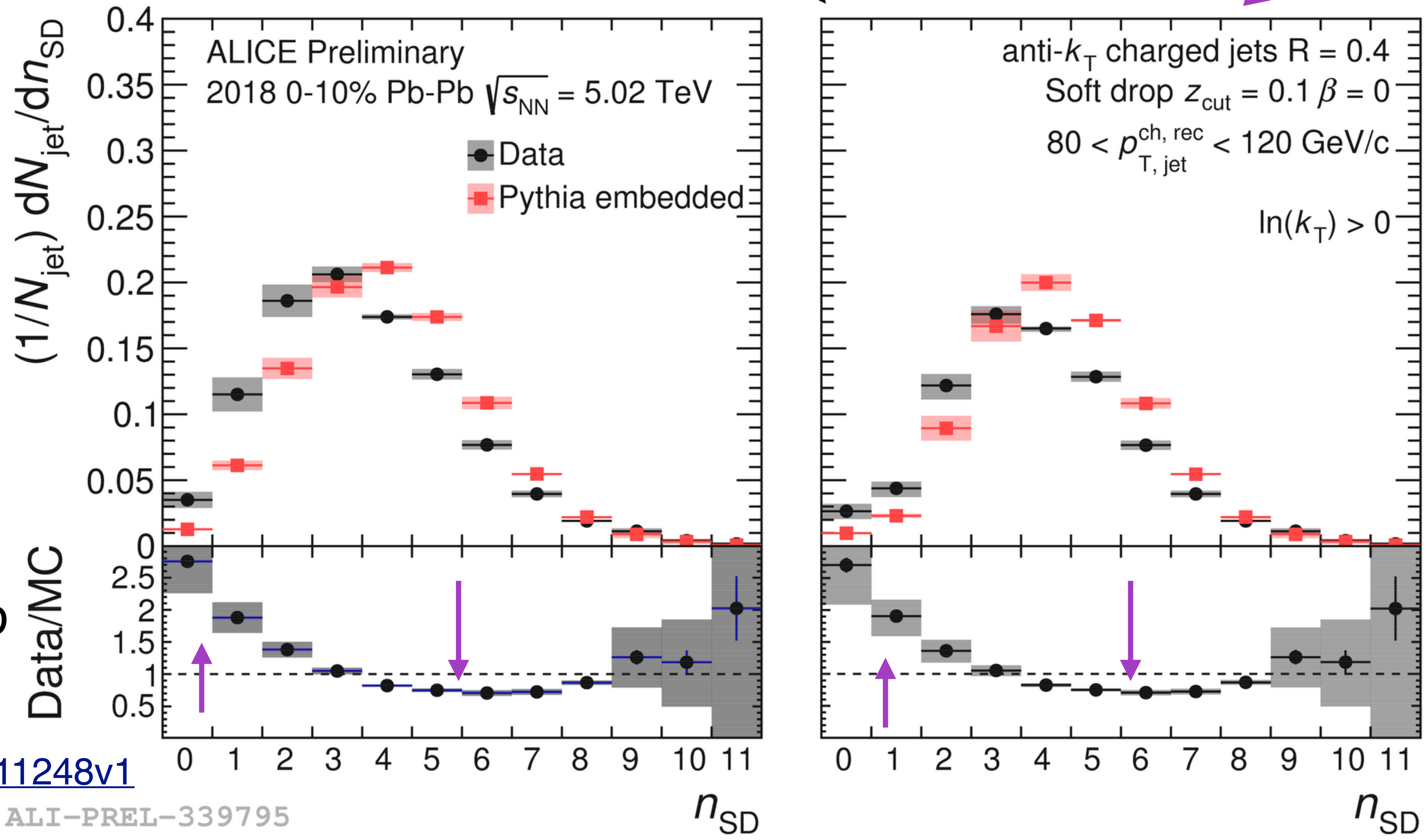


- New ALICE measurement at 5.02 TeV

- Modification: enhancement at small n_{SD} and suppression at intermediate n_{SD}

- Consistent with wider jets forming earlier and being suppressed in the medium, leading to more jets with lower n_{SD}*



*arXiv:1907.11248v1

Outlook

- A lot of progress has been made in background subtraction techniques
  - ➡ Keep working towards developing and trying new methods to increase precision and access inaccessible regions of phase space like large R and low p_T
- Jet substructure has also made a lot of progress
  - ➡ Need to implement better background subtraction techniques to reduce background and unfold
    - ▸ Using event-by-event constituent subtraction, for example
  - ➡ Improve our techniques to better access the hardest split
    - ▸ Dynamical grooming techniques (see Raymond Ehlers talk on Friday)
- In general improving our jet measurement tools will allow for more direct comparison of unfolded results to theoretical calculations to help constrain models (using JETSCAPE framework!)

Backup

Analysis Details

- Anti-kt R=0.4 jets within the acceptance of the TPC ($p_T^{track} > 0.15.$ GeV/c)

2017 pp data L_{int} = 18.0 nb^{-1} at 5.02 TeV

- No background subtraction
- Corrected for detector effects with unfolding to jets between 20-80 GeV/c

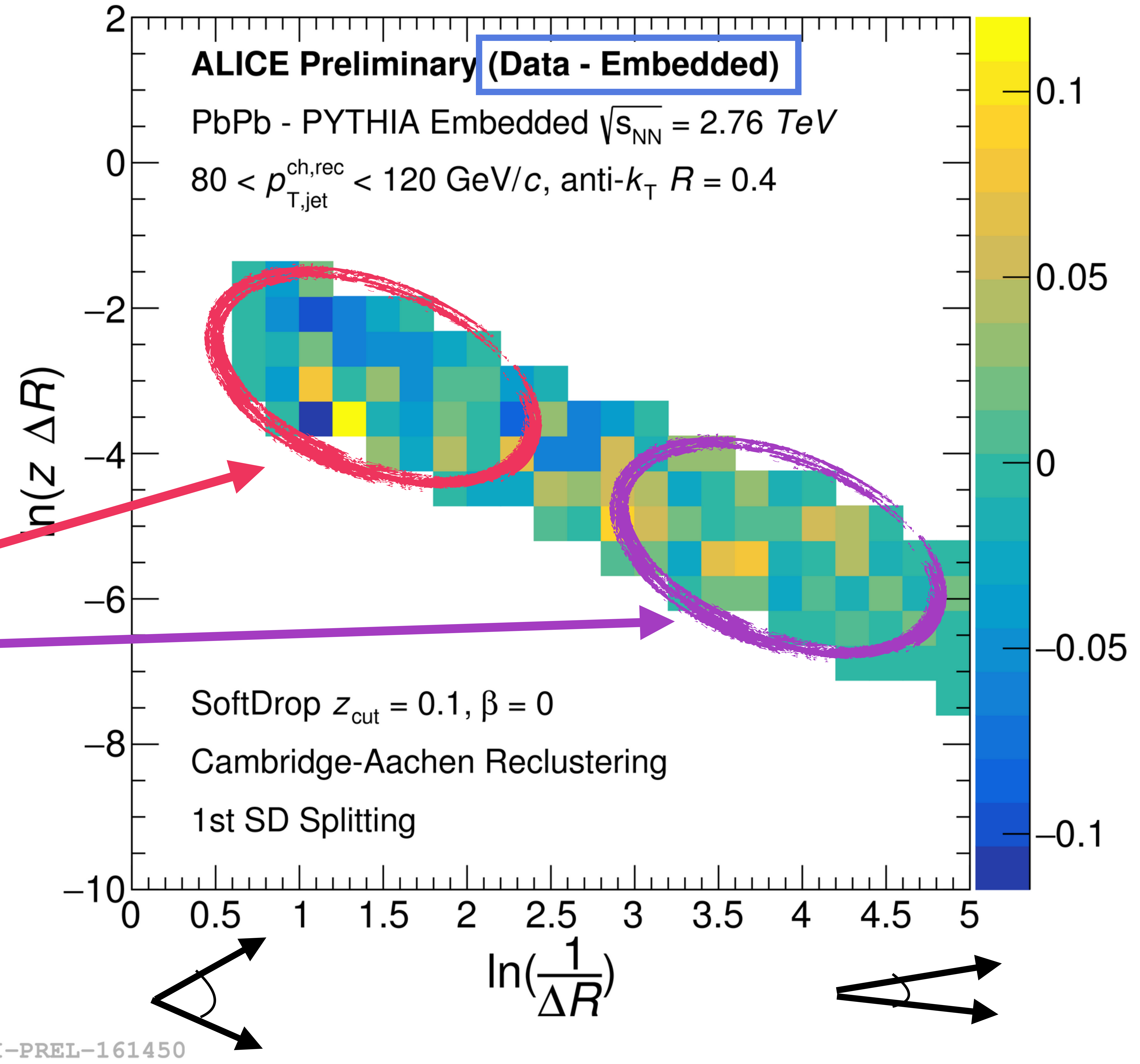
2018 0-10% Pb-Pb data at 5.02 TeV

- Jets between 80-120 GeV/c
- Substantial increase in statistics over previous ALICE substructure analysis at 2.76 TeV
- Jet-by-jet constituent background subtraction*
- Compared to embedded MC

*JHEP 06 (2014) 092

Exploring the Lund Plane in Run 1

- Previous ALICE measurement in 0-10% Pb-Pb collisions at 2.76 TeV
- Subtract the embedded simulations (MC) from the data in order to remove the effects from the large heavy-ion background
- Saw hint of suppression at large ΔR and enhancement at small ΔR
- *Investigate this further in the larger statistics 2018 data at 5.02 TeV*

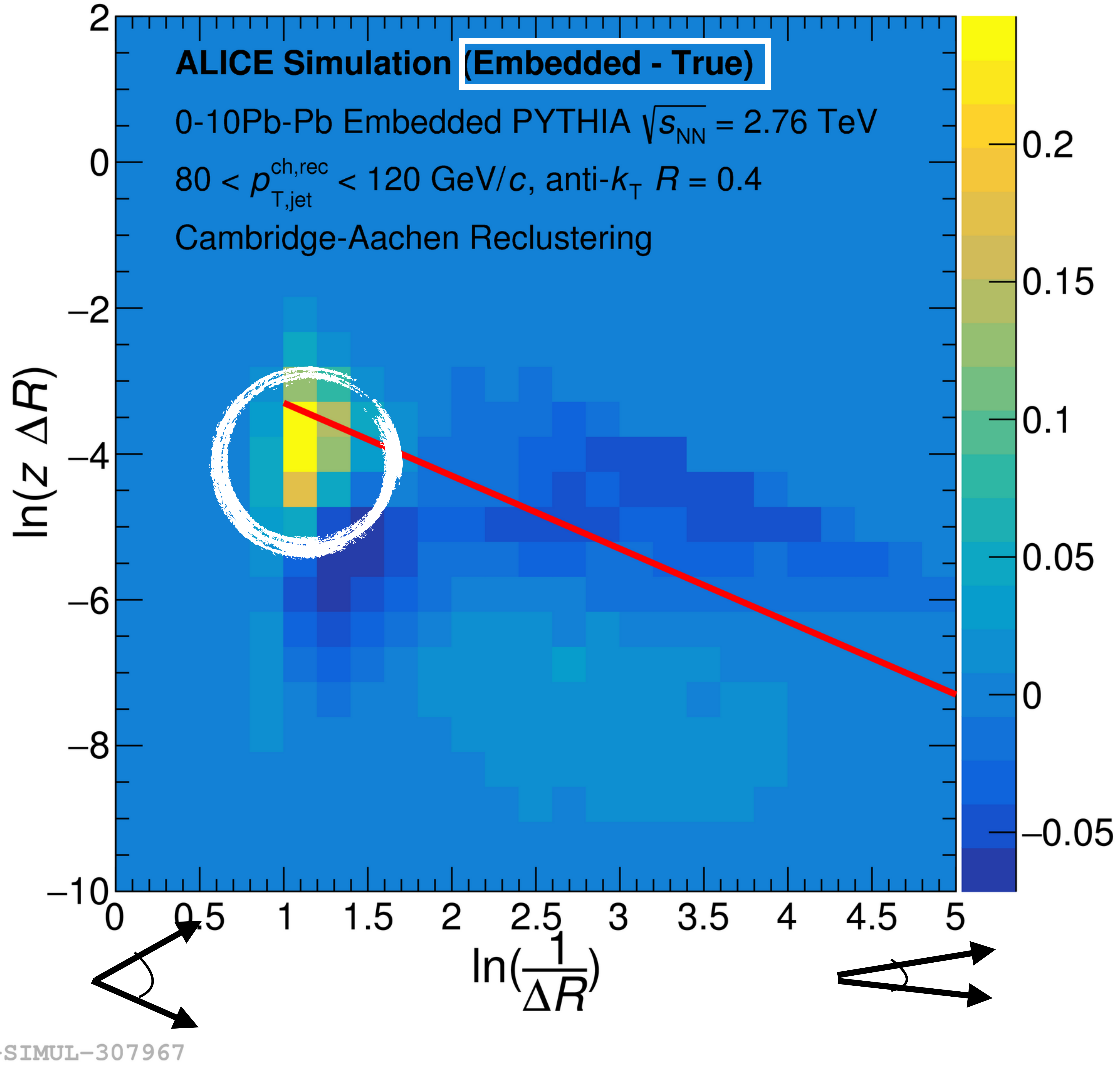


Laura Havener, Yale University

MC embedding background

- In Pb-Pb data need to account for HI background
- Embed detector level Pythia into Pb-Pb data
- **Embedded—True Pythia** shows enhancement of large angle splitting

Fake splittings!



Constituent subtraction

- Estimate background density in each event

$$\rho = \mathrm{med}\left(\frac{p_{\mathrm{T,jet}}^{\mathrm{raw,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}}\right)$$

$$\rho_m = \mathrm{med}\left(\frac{m_i}{A_{\mathrm{jet}}^{\mathrm{i}}}\right)$$

- Add infinitesimally small ghosts to the event
- Set the p_T for each ghost to negative values

$$p_{\mathrm{T,g}} = A_{\mathrm{g}}\rho$$

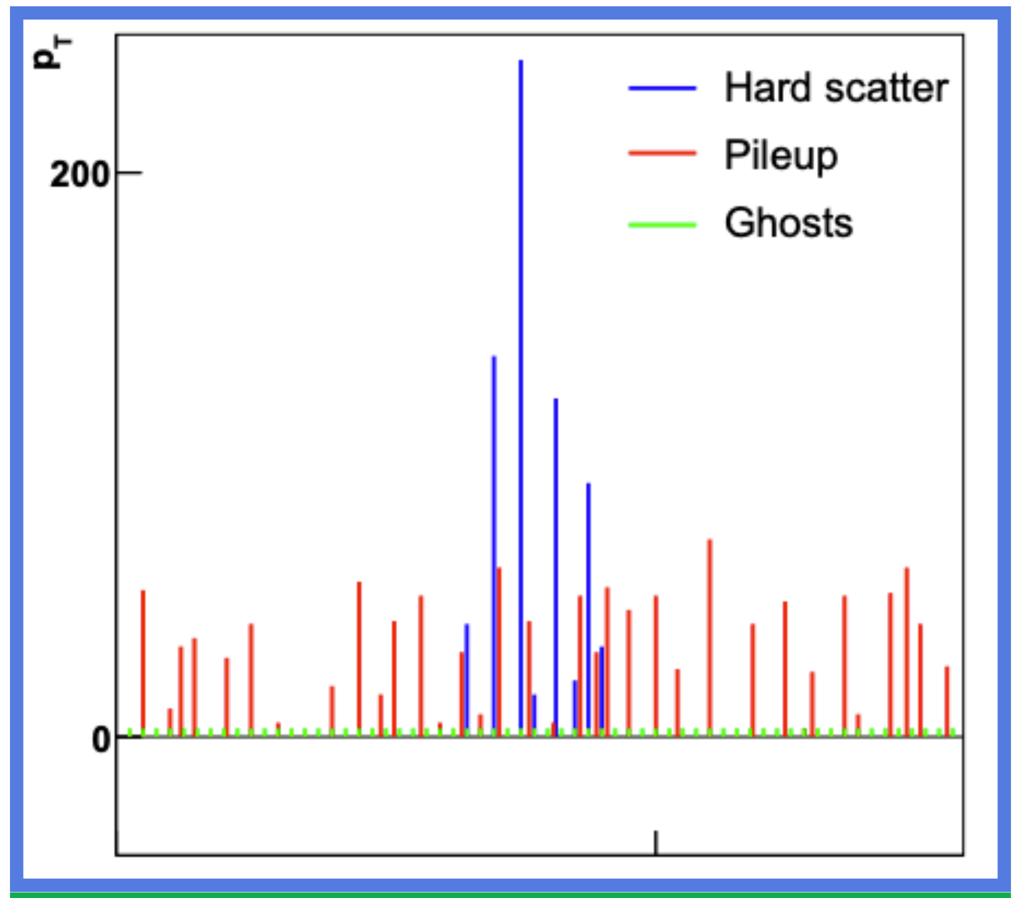
$$m_{\mathrm{g}} = A_{\mathrm{g}}\rho_m$$

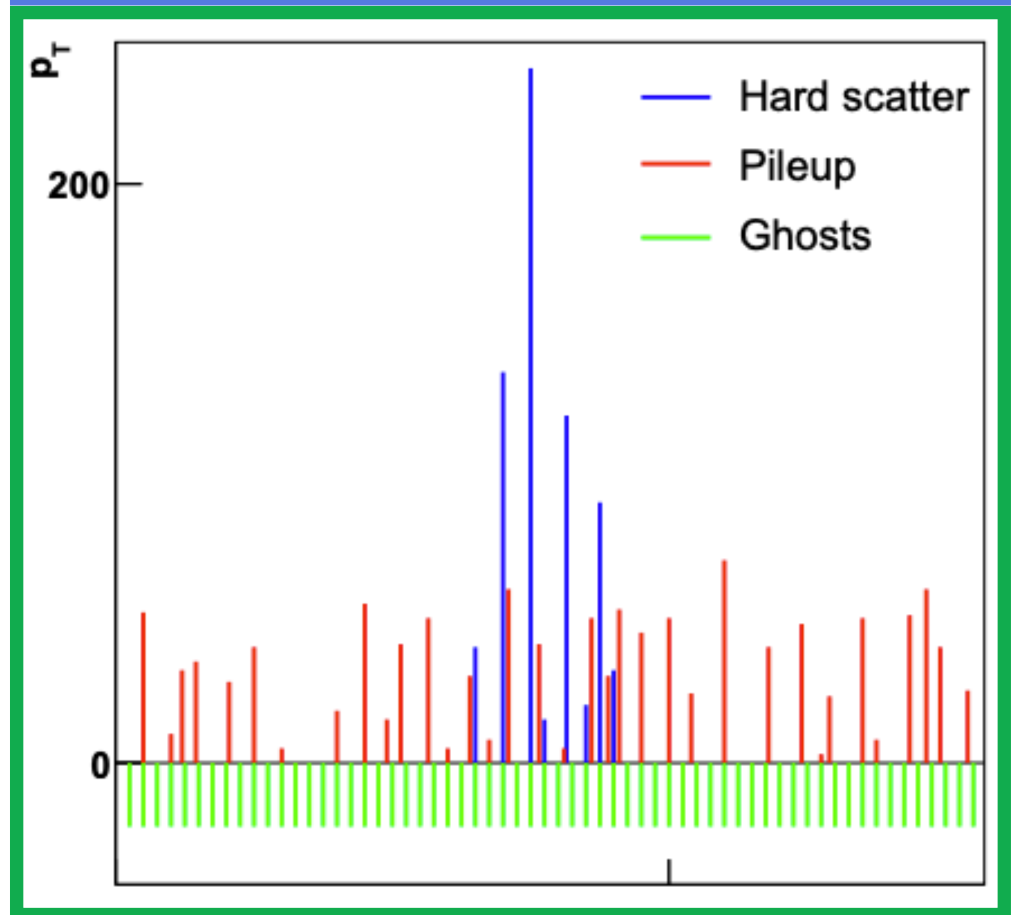
- Calculate distance between each particle and ghost for each pair and sort in ascending order
- Iteratively change the momentum and mass of each ghost/particle until no more pairs remain

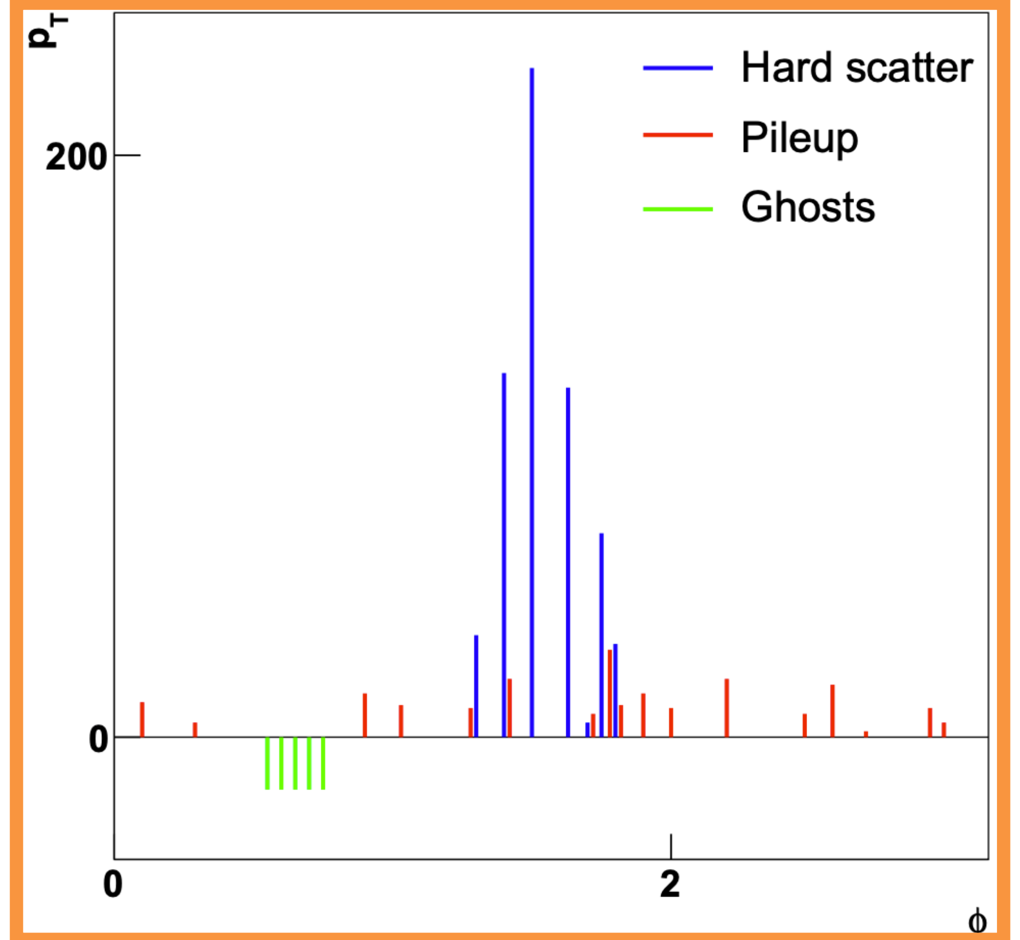
if ($p_T > p_T^g$) $p_T = p_T - p_T^g$, $p_T^g = 0$ $p_T^g = p_T^g - p_T$, $p_T = 0$

- Discard particles with 0 momentum

JHEP 1908 (2019) 175



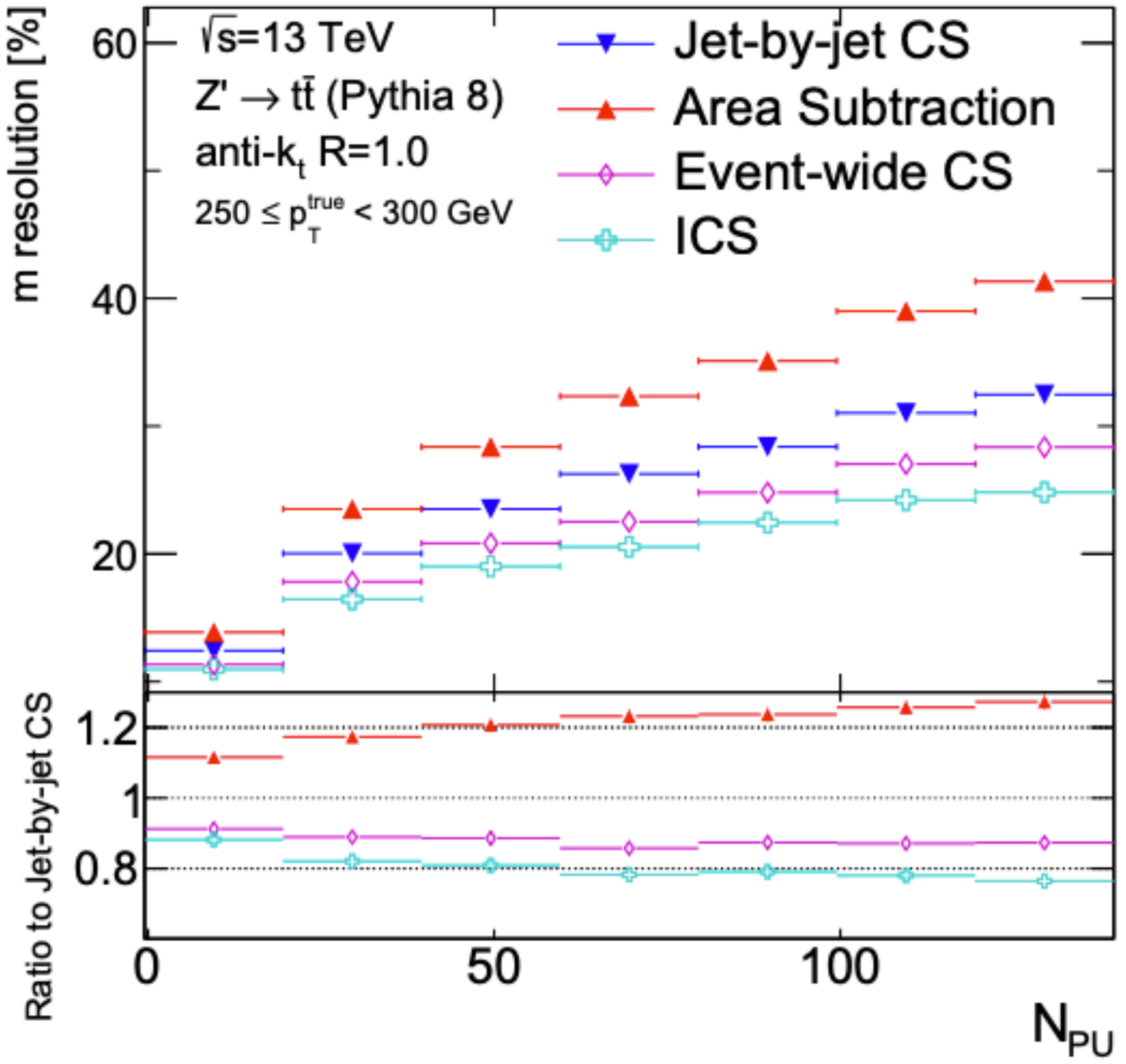




Laura Havener, Yale University

Constituent subtraction

- Jet-by-jet constituent subtraction:
  ➡ Only ghost are added in jets in the event found with a reclustering algorithm
- Event-by-Event constituent subtraction:
  ➡ Ghosts are added to the entire event with a finite value where the ghosts can be unmatched
- Event-by-Event iterative constituent subtraction:
  ➡ The missed are redistributed to reduce bias



- Improved resolution with each improvement for the mass
- Experiments working to incorporate these in HI measurements

JHEP 1908 (2019) 175

Background subtraction

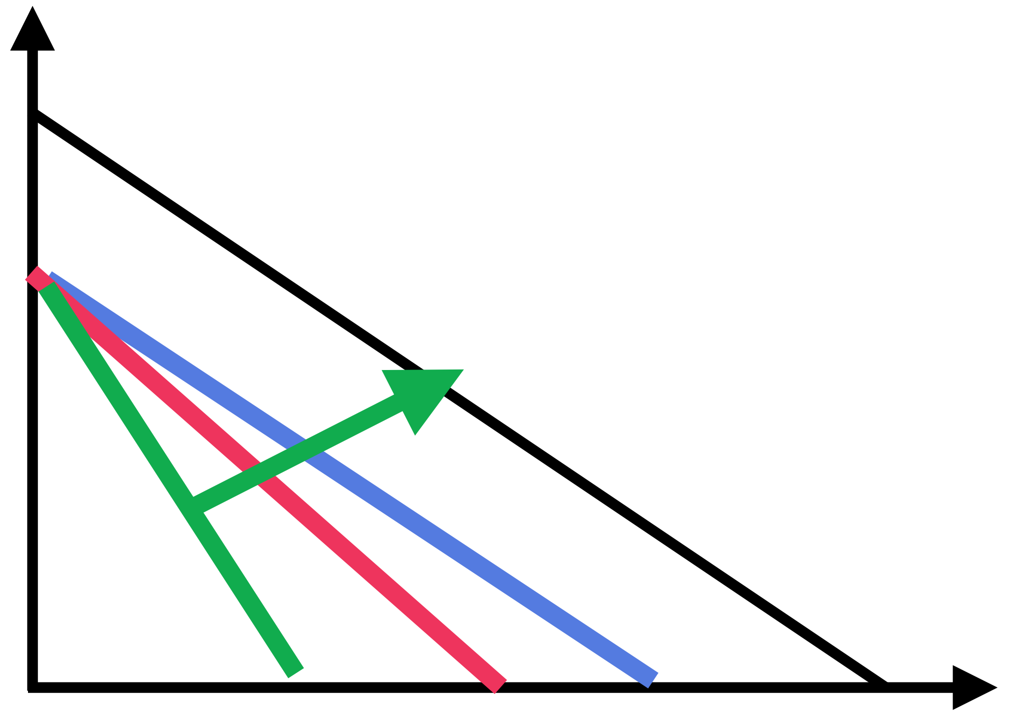
Impact of the jet-by-jet constituent subtraction on substructure variables

Laura Havener, Yale University

θ_g: subjet separation

- pp collision data at 5.02 TeV L_{int} = 18.0 nb^{-1} unfolded for detector effects

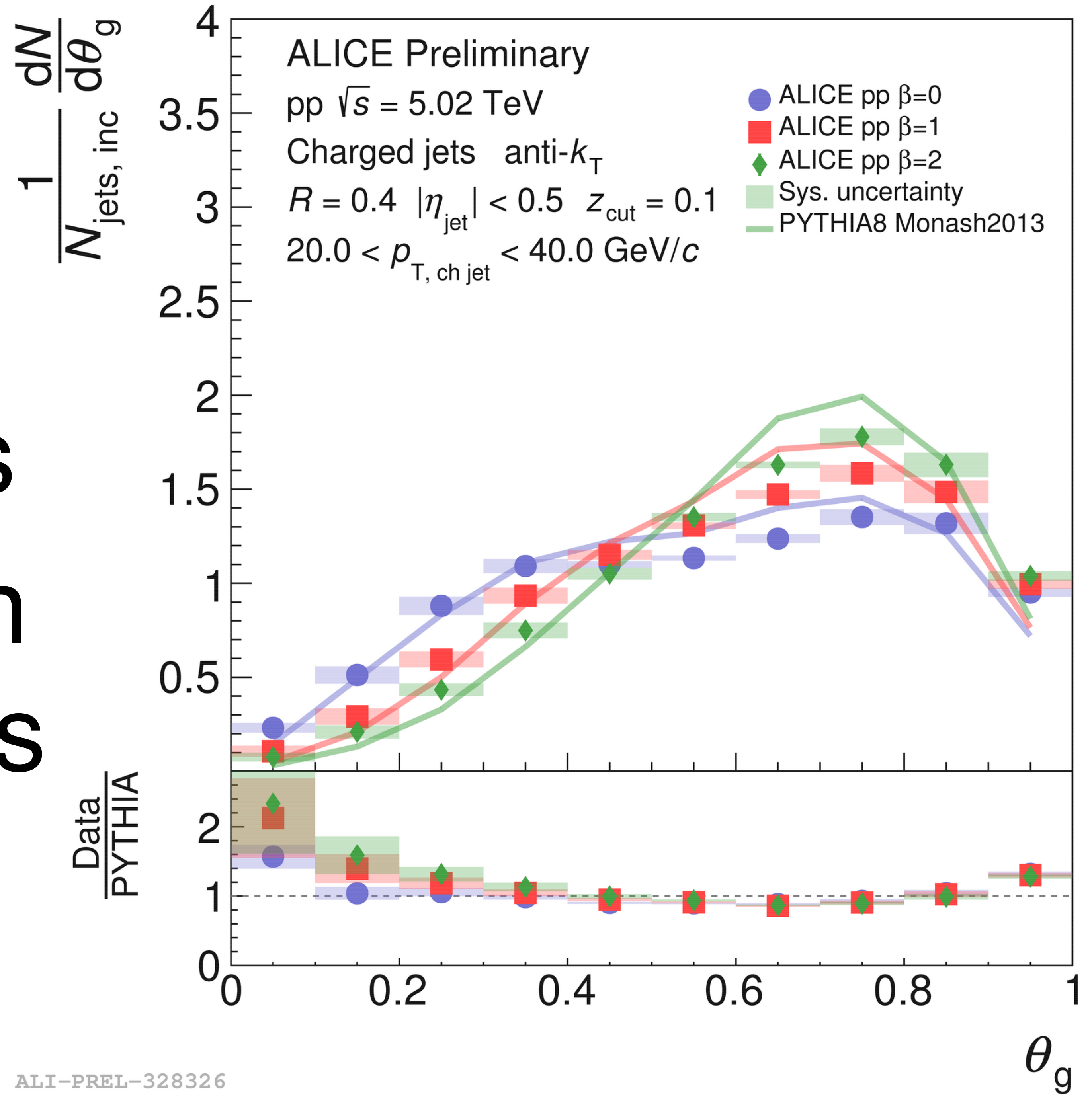
$z_g > z_{cut}\,\theta^{\beta}$

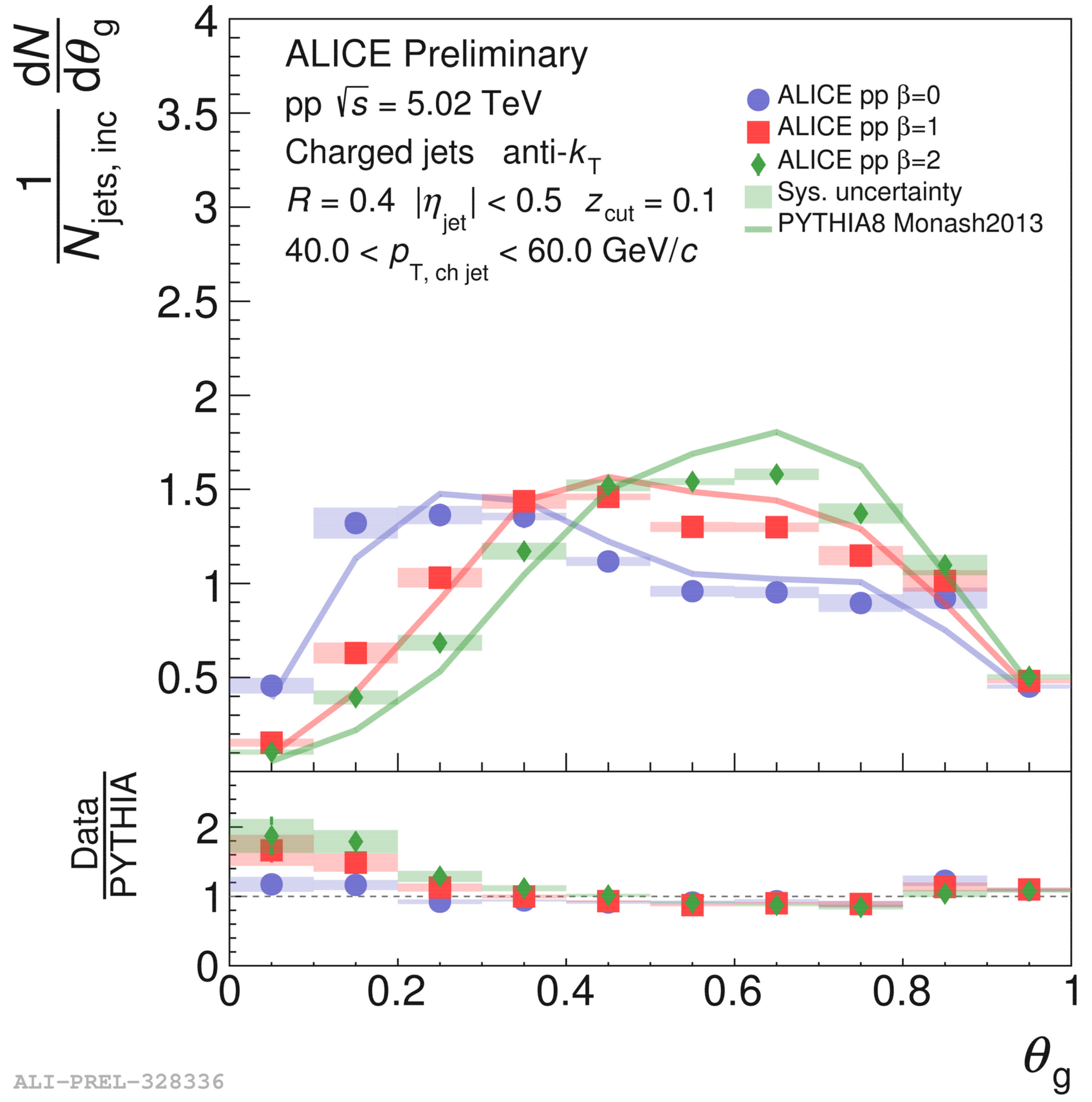


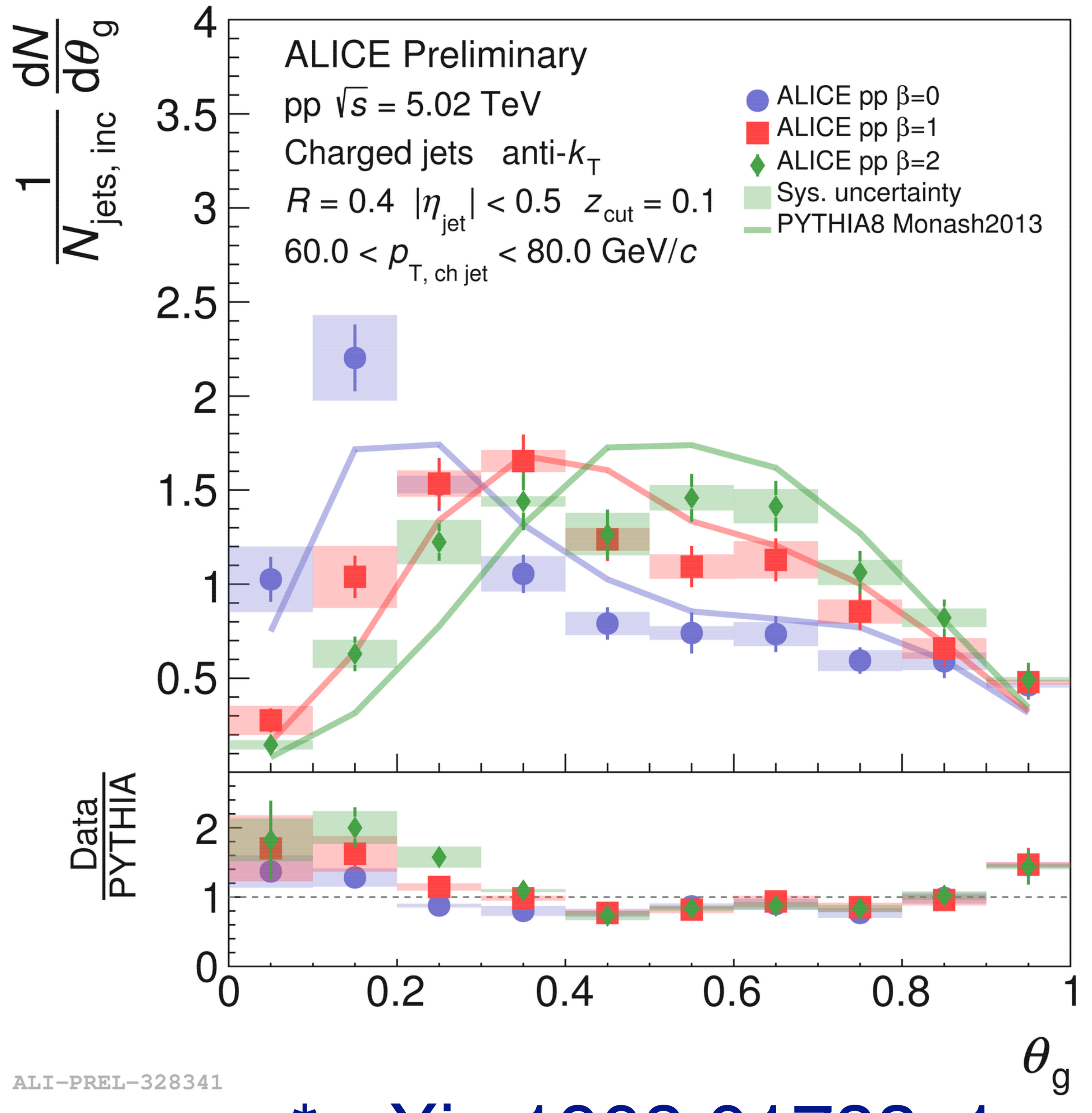
$$\theta_g = \frac{R_g}{R} = \frac{\sqrt{\Delta\eta^2 + \Delta\phi^2}}{R}$$

- Dependence on grooming (β) measured:
  - *Useful to constrain pQCD calculations and non-perturbative effects**

- Increasing β increases contribution of wider jets





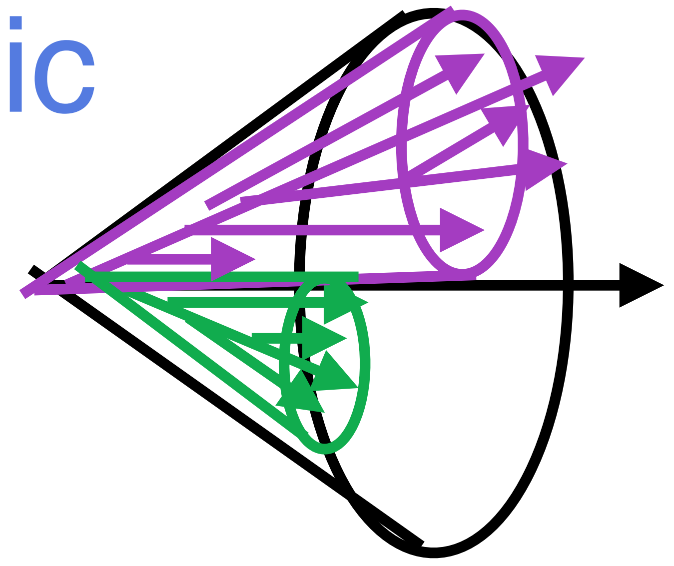


*arXiv:1908.01783v1

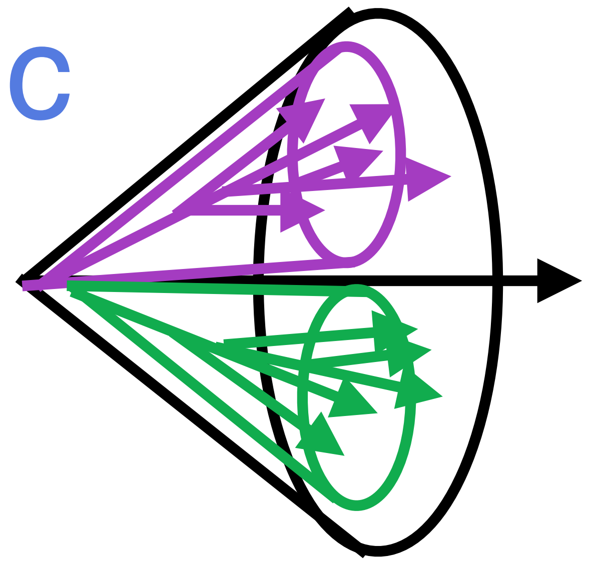
z_g: jet splitting

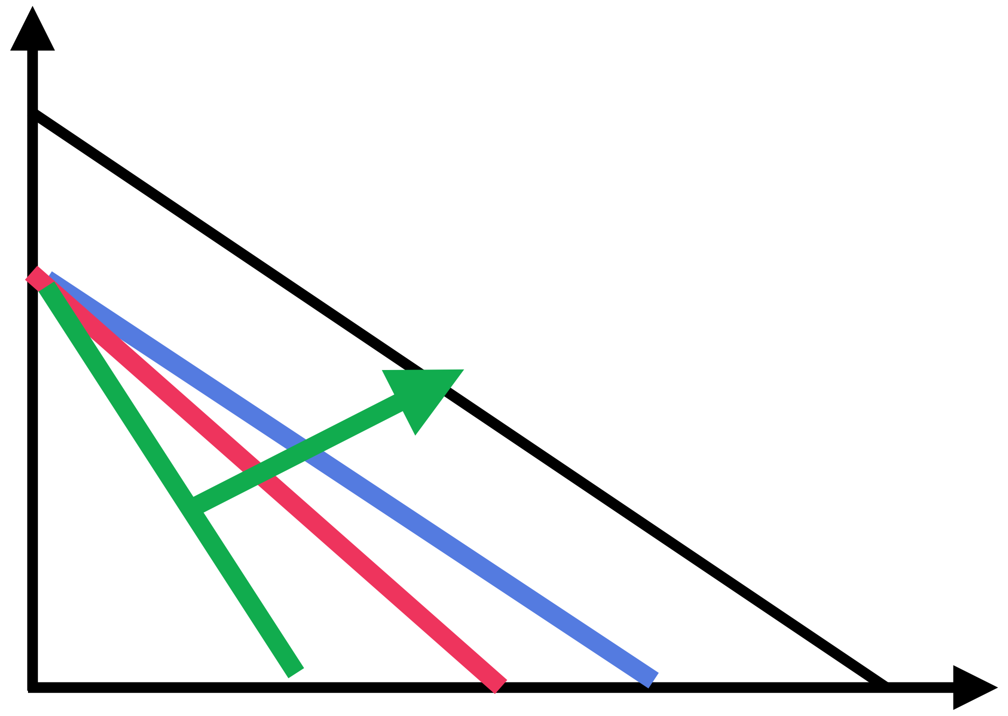
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

asymmetric splitting: low z_g

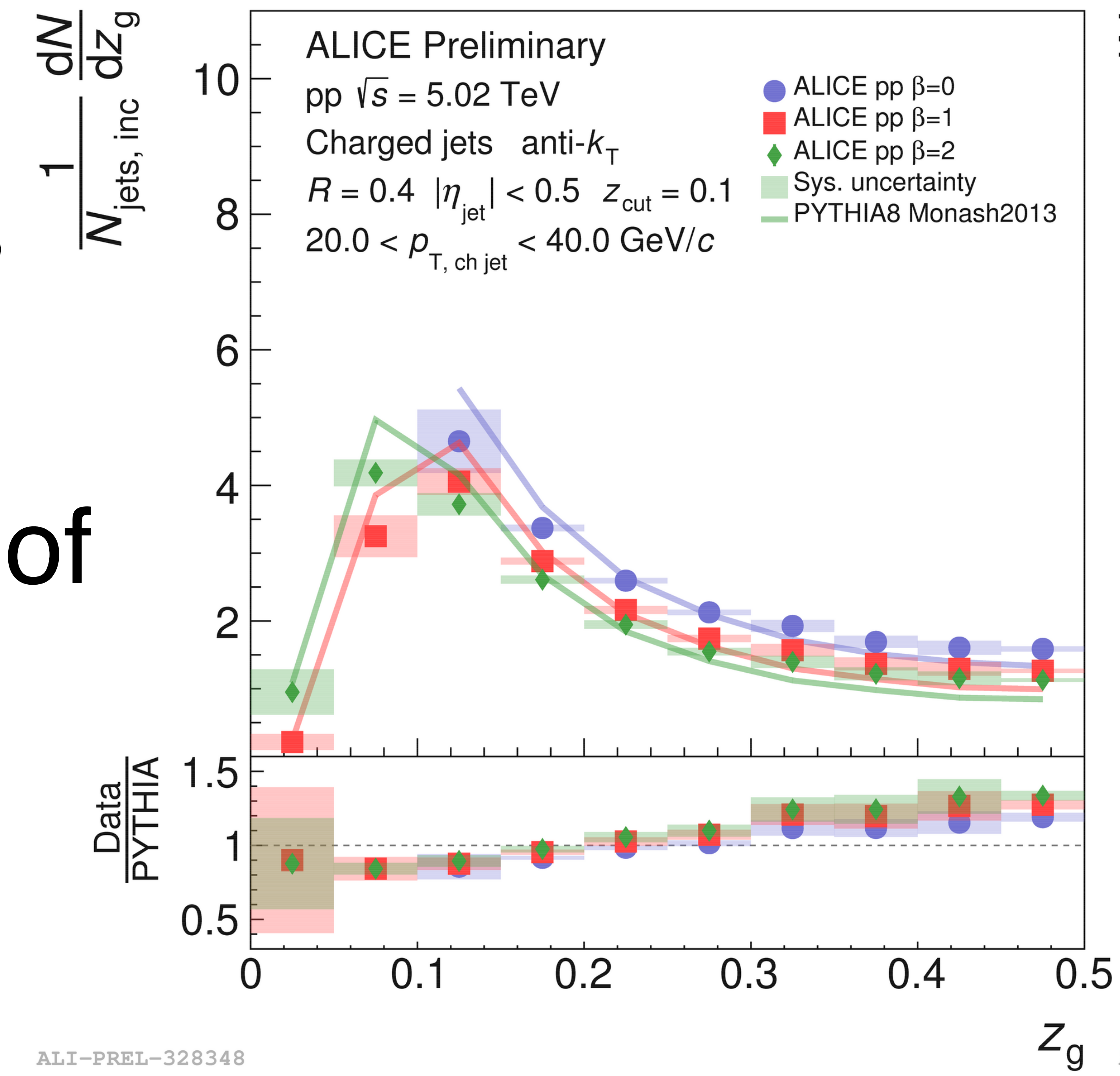


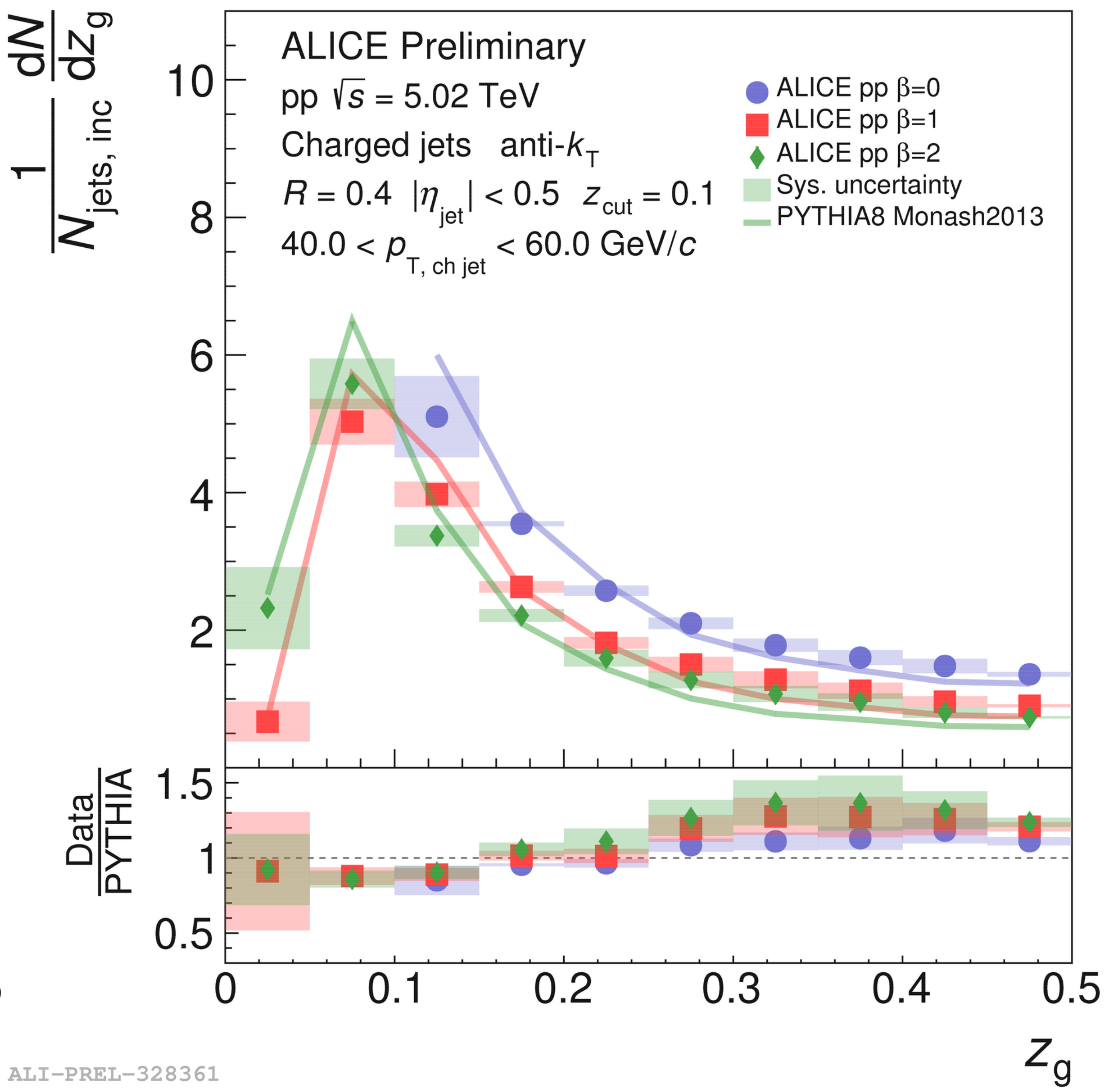
symmetric splitting: high z_g

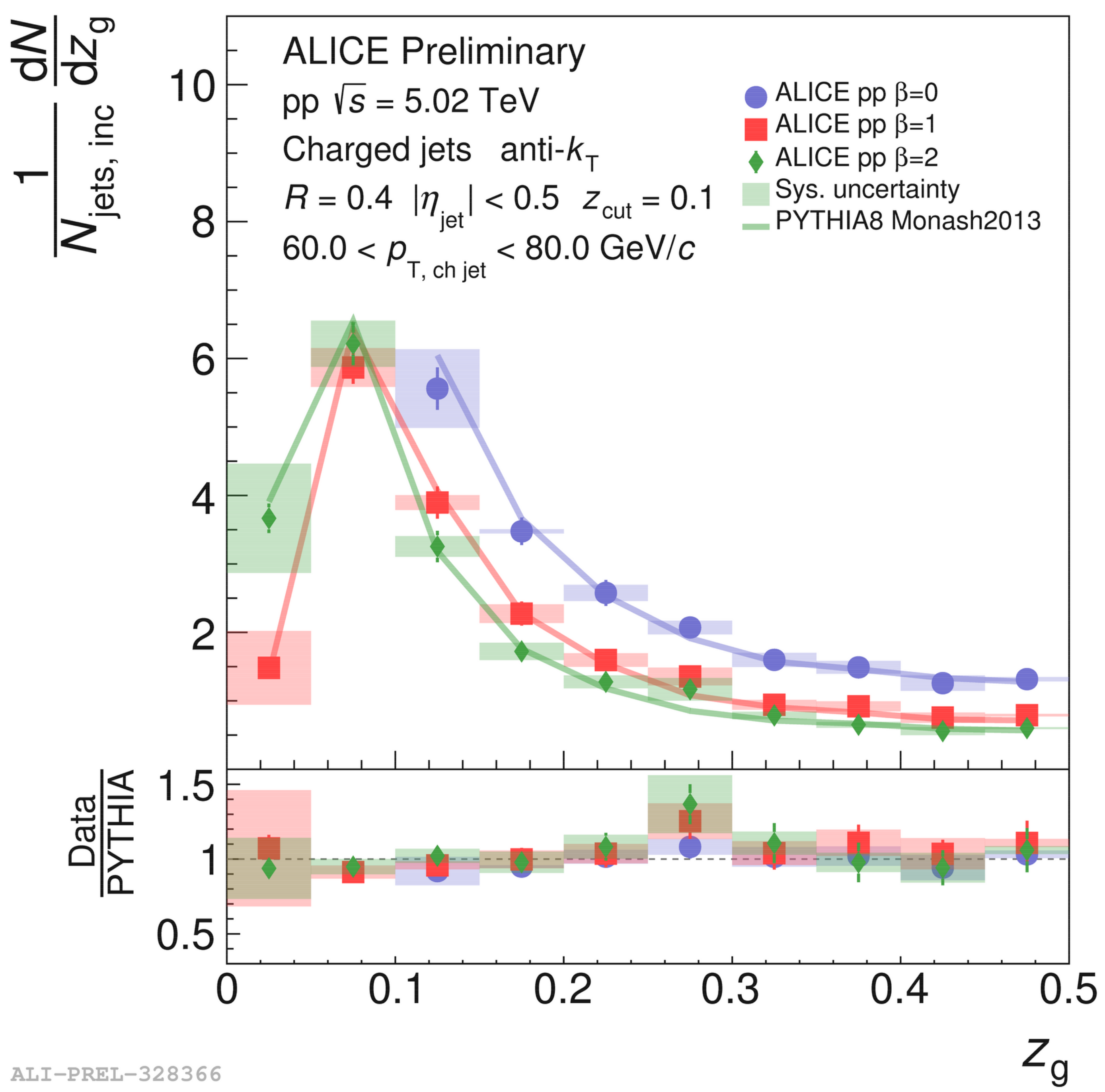




- Increasing β increases contribution of asymmetric jets



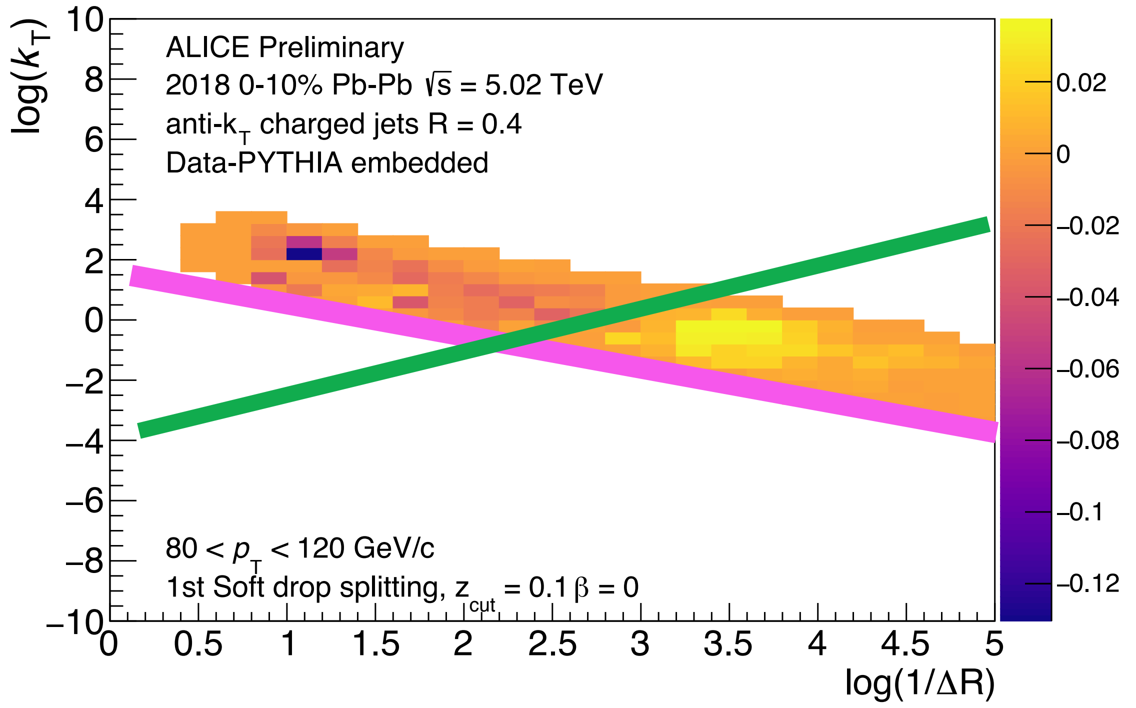




- Both θ_g and z_g mostly consistent with PYTHIA8
- Serve as baseline for future unfolded Pb-Pb measurements

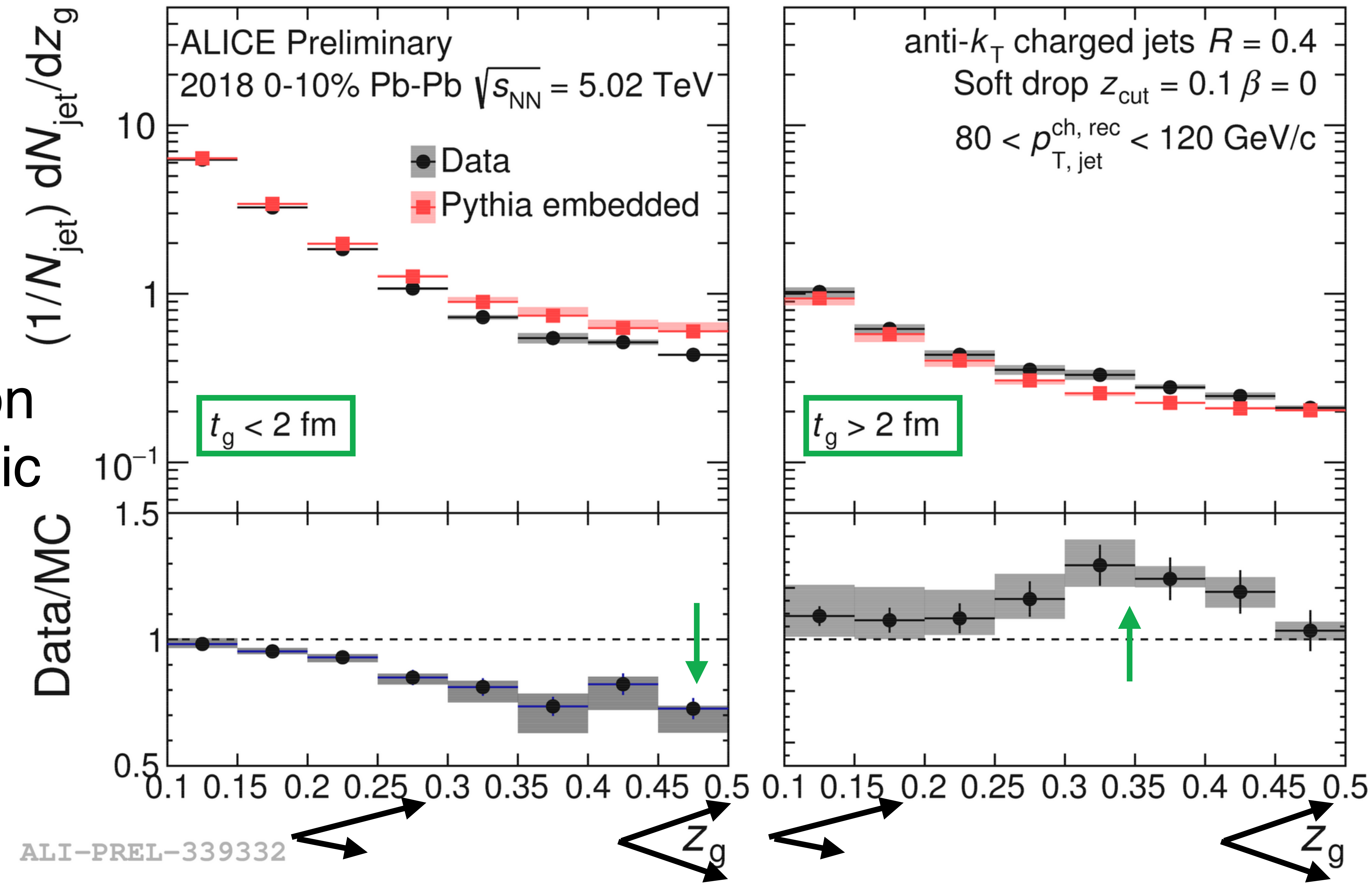
z_g: groomed time

$$t_g = \frac{1}{(1 - z_g)k_{Tg}R_g}$$



Early splittings

Late splittings



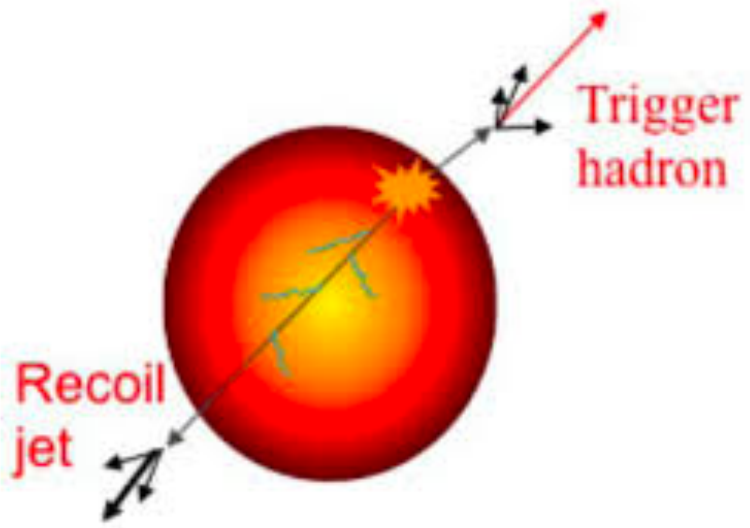
- Suppression of symmetric splittings?

- Enhancement of splittings?

- *Similar trend as angular cuts*

Laura Havener, Yale University

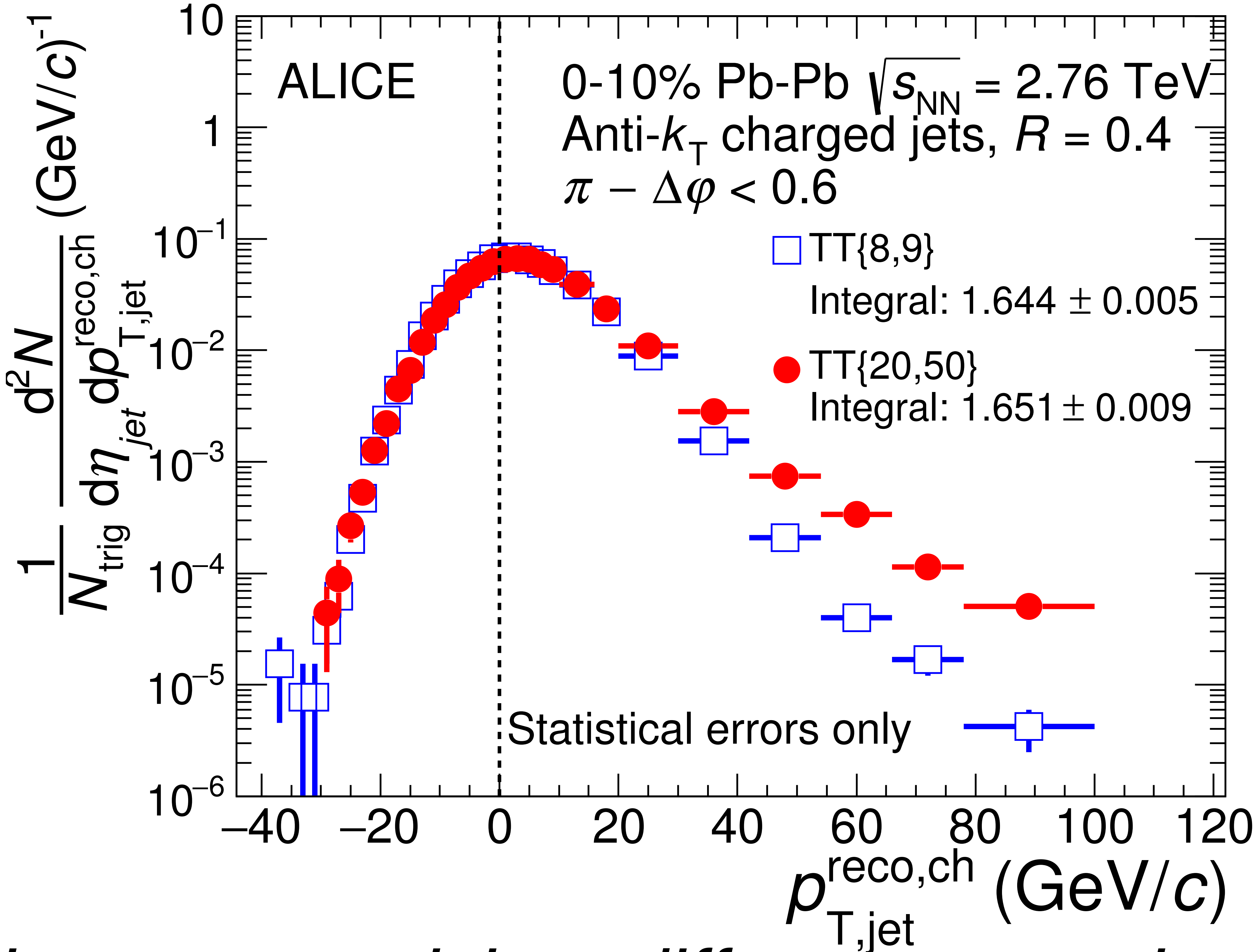
Removing fake splittings



- Try ways of removing these fake splittings from combinatoric jets
  - Try using semi-inclusive hadron+jet measurement as done for the 2-subjettiness
    - Difference in recoil jet yield from two different high p_T hadron trigger classes

      ΔY = Y1 - Y2

      ΔY is combinatoric free!
    - Need to do unfold in 2D in jet p_T and groomed jet variable
      - *Other ways?*

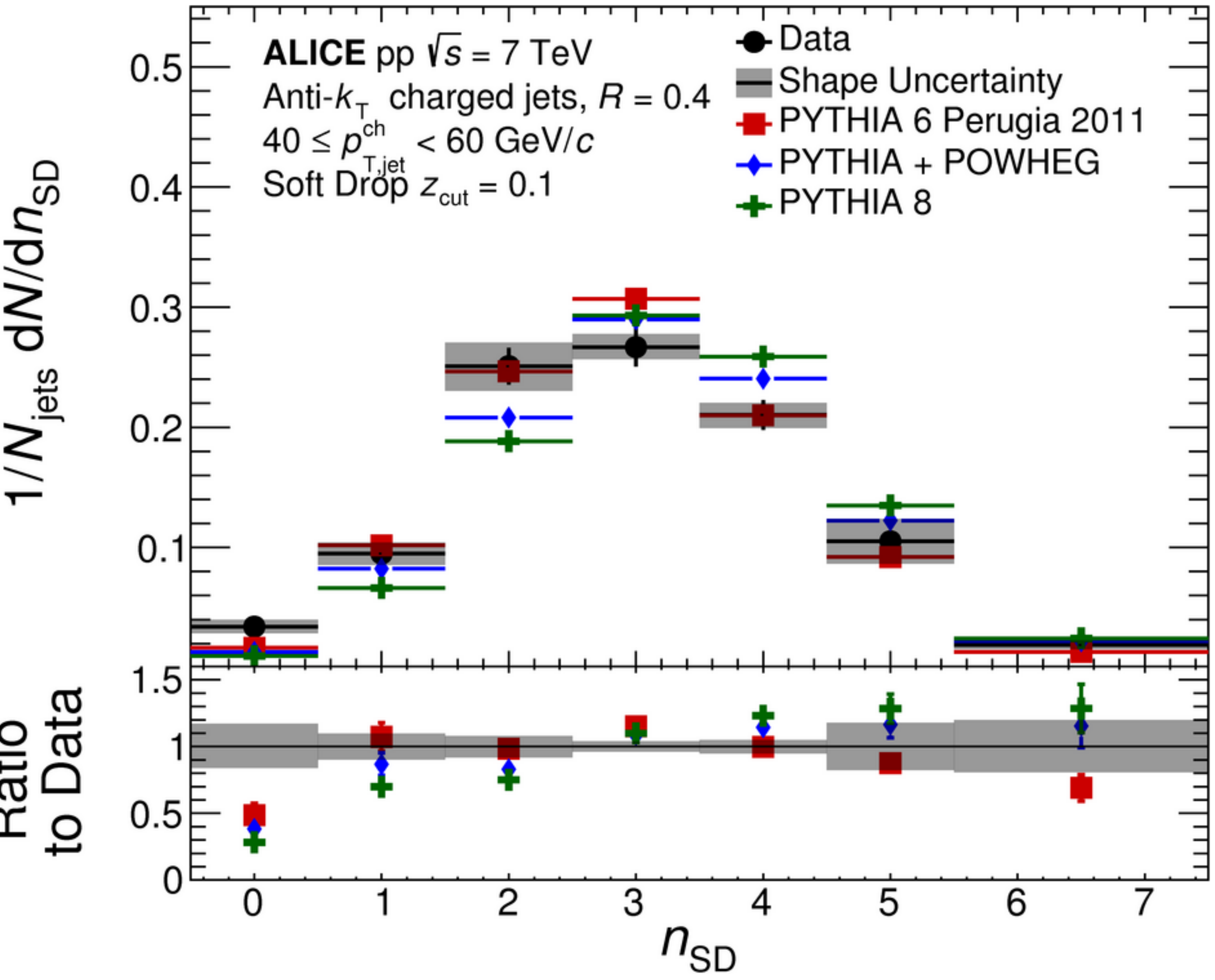


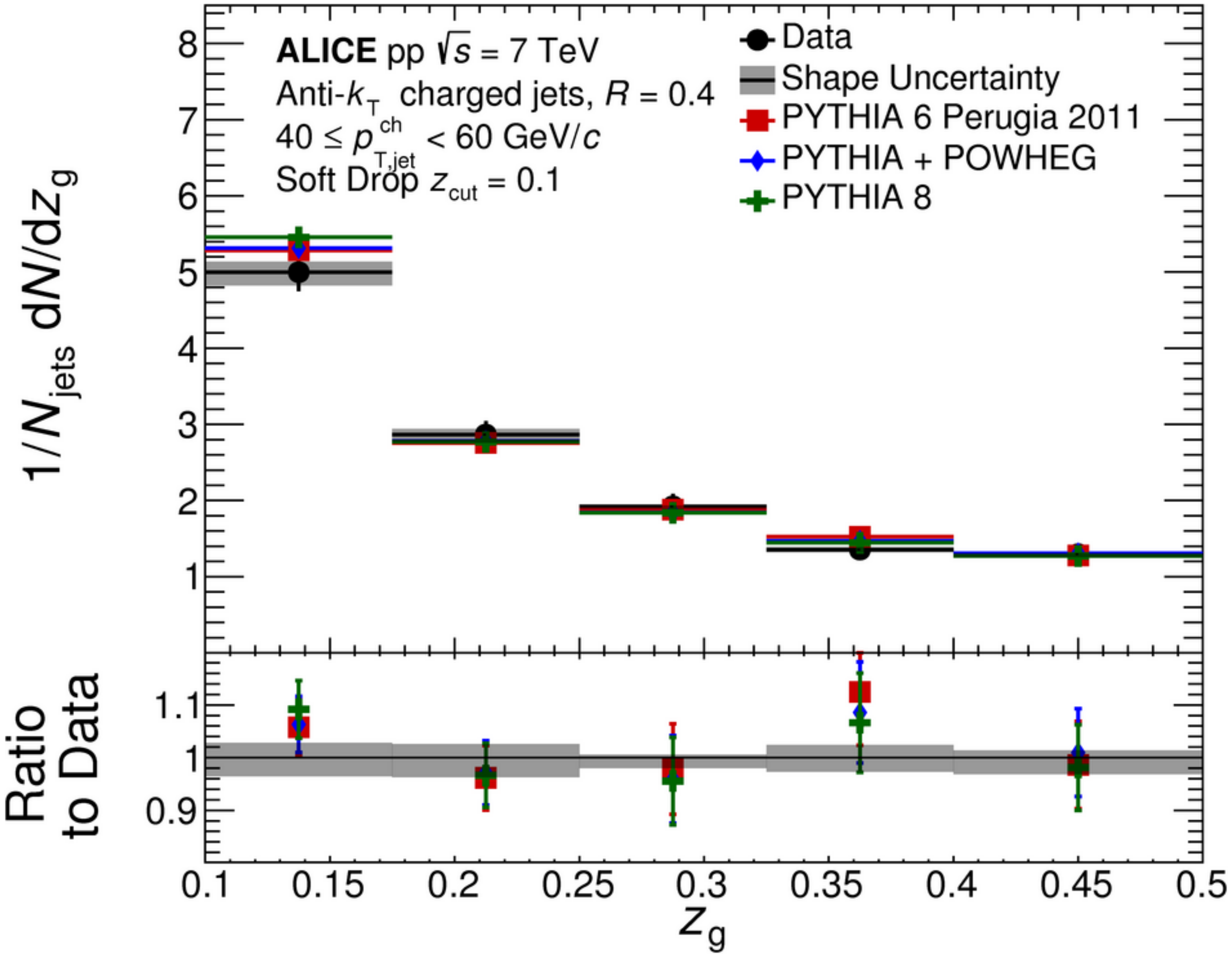
Machine learning, event mixing, different groomings, other subtraction methods, etc.

Systematic Uncertainties

- Data:
  - ➡ Tracking inefficiency: the tracking efficiency was lowered in the embedding by 4% and the effect was evaluated on the embedded MC and apply to data
  - ➡ Varying cuts of tf, ln(kt), and dR by +/-10%
  - ➡ Reweighing the prior by Herwig/Pythia to account for differences in the model
  - ➡ Double counting

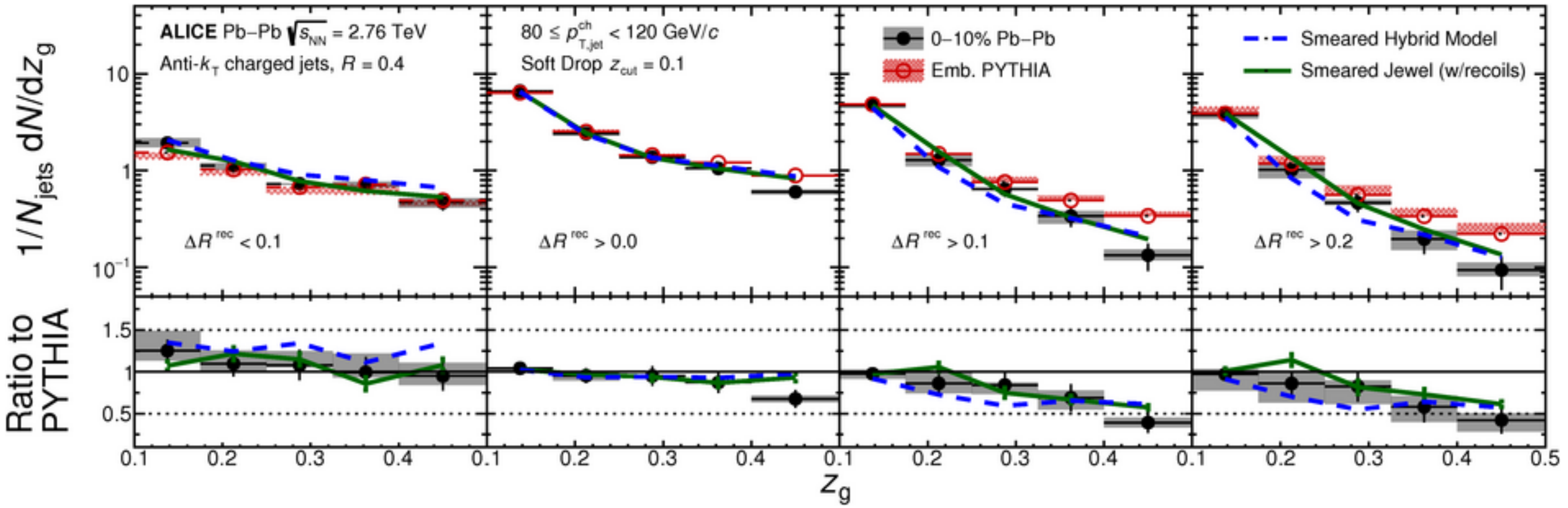
z_g and n_{SD} in pp collisions at 7 TeV





arXiv:1905.02512v1

z_g Pb-Pb collisions at 2.76 TeV



arXiv:1905.02512v1

Formation time

- Plan to explore if we can select on early or late splittings using the formation time calculated from CA declustering?
  ➡How well does it correlate with QCD formation time?

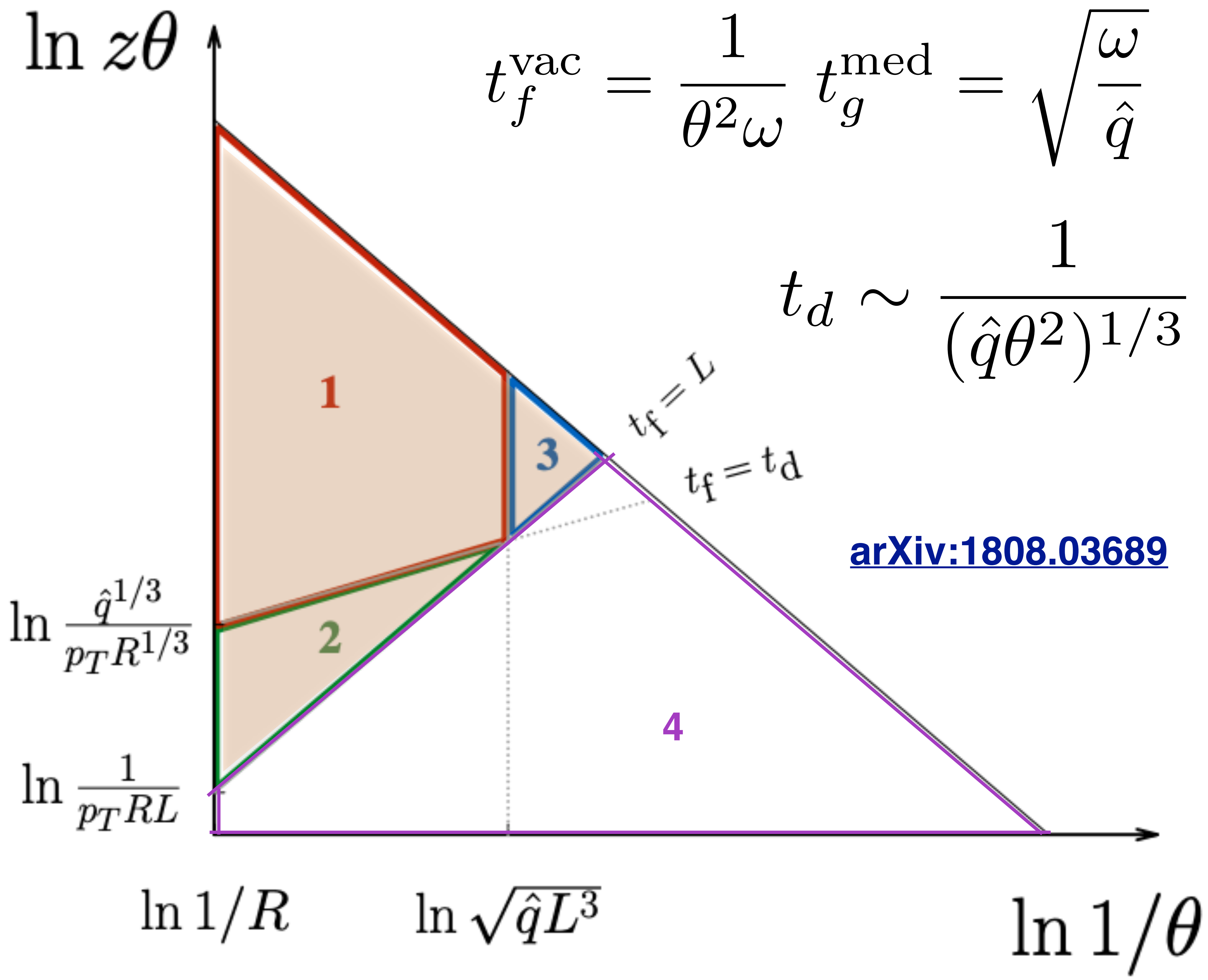
see L. Apolinário EPS-HEP

1: Vacuum splitting in-medium that is resolved (decoherence)

2: Medium-induced splittings

3: Splitting in-medium that isn't resolved (coherence)

4: Vacuum splitting outside of medium



arXiv:1808.03689

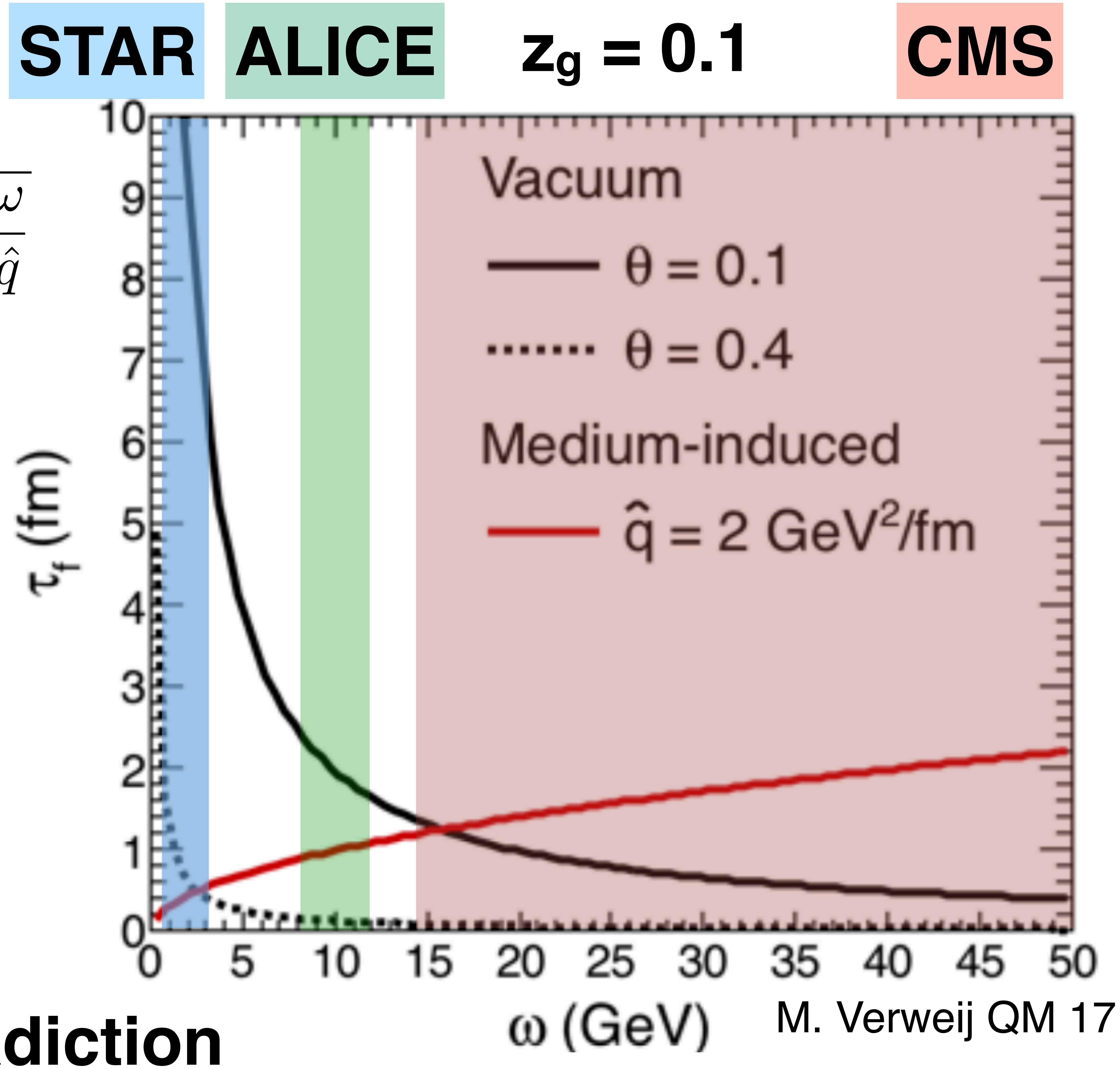
Caveat: this has a model dependence

Jet splitting: RHIC vs. LHC

- **Formation time for gluons in vacuum or medium**

$$t_f^{\text{vac}} = \frac{1}{\theta^2 \omega} \quad t_g^{\text{med}} = \sqrt{\frac{\omega}{\hat{q}}}$$

- **Wider splittings form earlier in a vacuum so more likely to see the medium**
- **Low energy gluons emitted later and may not see medium (STAR vs. LHC)**



M. Verweij QM 17

- **RHIC and LHC not necessarily in contradiction because they probe different formation times**